SOIL AMENDMENTS AND TILLAGE DEPTH IN MATTED ROW STRAWBERRY FIELDS AND THEIR EFFECTS ON SOIL HEALTH INDICATOR TESTS AND YIELD

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Master of Science

By

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ABSTRACT

Strawberries are an economically important crop in the United States worth more than $2 billion annually. Many studies have correlated strawberry growth and yield with various aspects of the soil. Mostly these studies involve the effects of individual soil nutrients, and to a lesser extent soil physical properties. Studies examining the impact of the biological components of soils mostly focus on pathogens and not beneficial organisms. Agronomists recently introduced the concept of "soil health" in which chemical, physical, and biological components of the soil are considered simultaneously. Selected indicators are used to predict the performance of a crop and identify which components should be modified to positively impact crop growth and yield. A healthy soil is highly functional in both the short term and long term and is able to support human needs and ecosystem sustainability. This study tests the hypothesis that in a perennial strawberry field the C:N ratio of soil amendments and tilling deep or shallow would affect soil biological health indicator tests and that these would be correlated with yield. Soil biological health indicator tests were not correlated with yield although treatments did affect both indicator tests and yield. The strawberries grown in straw-amended soil had the lowest plant growth and yield but not lower biological soil health indicator test results. Sawdust-amended soil had higher soil biological health indicator test results from increased microbial activity, but had the same yield as unamended soil. Alternative soil biological health indicator tests that are correlated with strawberry yield might be more appropriate for perennial crops. We hypothesized that decreased strawberry growth in straw-amended soil was due to either a chemical leachate, an antagonistic microbial community, or a physical barrier to root growth. These hypotheses were tested in the greenhouse. The reduced strawberry growth in the field was not replicated in the greenhouse as no treatment had an effect on plant growth. The reason for reduced plant growth in straw-

amended plots in the field is still unclear, but there are benefits to using straw such as insulating berries over the winter, suppressing weeds, preventing soil from getting on the fruit, and reducing plant diseases. Growers should continue to use straw until an appropriate alternative solution is found.

BIOGRAPHICAL SKETCH

Maria Gannett grew up in Cape Cod, Massachusetts. She traveled to Fredericksburg, Virginia to study Environmental Sciences at the University of Mary Washington. However it was during her summers, working back home at the University of Massachusetts Cranberry Research Station in Wareham, where she realized her passion for agriculture. Agricultural research was an area she could foster her curiosity in science, look for practical solutions to problems affecting her community and environment, and help to produce the healthy food she loved to eat.

After graduating with her Bachelor of Science in 2010, Maria joined the Peace Corps where she was an agroforestry volunteer in Senegal, West Africa. Those years confirmed that agriculture was where she wanted to stay. She came to Ithaca, New York, in 2013 to begin her Master of Science degree in Horticulture.

Maria enjoys any excuse to be outside: running, hiking, swimming, and skiing. She also makes sure to enjoy the fruits of her labor through cooking.

Dedicated to my Aunt Donna

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The path of my life has crossed that of countless others and I certainly would not have made it to this point without their support, some of whom I have never even met. Unfortunately I am supposed to keep this section to a page or two, so I cannot go back and thank everyone who has helped me grow into the person I am today, and therefore I will start with my time at Cornell. Although, I do not think I would have even been inspired to apply to graduate school without working for Dr. Frank Caruso, so thank you.

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CHAPTER 1

THE SOIL HEALTH CONCEPT IN THE CONTEXT OF MATTED ROW STRAWBERRY PRODUCTION

SOIL HEALTH

The Concept

Soils are composed of minerals, organic matter, air, and water. The soil health concept attempts to quantify those soil characteristics in order to qualify how well the soil will sustain a healthy community and environment (Figure 1.1).

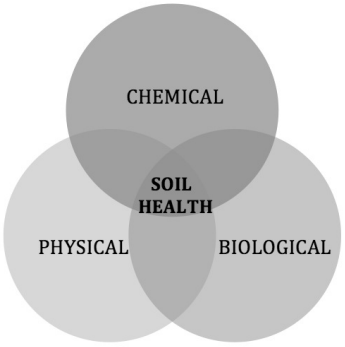

Figure 1.1 Visual interpretation of soil health: the intersection of chemical, physical, and biological components of soil.

Soil health has been defined by the Soil Science Society of America as "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation" (Doran et al. 1994).

There are two components to soil health: dynamic and inherent soil quality (Gregorich et al. 1994, Karlen et al. 2003). Inherent soil quality, or intrinsic soil composition, is a product of underlying bedrock and soil formation processes. Dynamic soil quality refers to the soil qualities

that respond to management. Often *soil health* refers only to dynamic soil quality, since inherent soil quality cannot be changed. Despite the fact that inherent soil quality cannot be altered, it has a dramatic effect on the functionality of a soil and all *dynamic* soil quality indicators must be compared only to soils with similar *inherent* soil quality characteristics. In this paper soil health and soil quality will be used interchangeably and both will refer only to dynamic soil quality.

Quality of a soil is a concept that has been important to farmers since the beginning of agriculture. Soils were deductively called "rich," "light," and "prosperous," but inductive discussions of soil health as the measureable gestalt of chemical, physical, and biological properties of soil really increased in the 1990s (Karlen et al. 2003, Warkentin 1995). In 1993 the National Research Council Committee completed a study on the impact of our agricultural practices on soil and water resources. One of their main recommendations was to increase research and policy incentives to conserve and enhance soil quality. In 1994 a joint symposium including the Soil Science Society of America, the American Society of Agronomy, and the North Central Region Committee on Soil Organic Matter met to define soil quality and to relate the different soil disciplines to the idea of soil quality (Doran 1994). Since the definition of soil health is broad, the idea of soil quality can also be applied to a variety of systems: farms, forests, parks, residential areas, and commercial land. Therefore, the soil quality concept has become popular amongst a variety of soil related disciplines and its applications are increasing (Doran and Zeiss 2000, Liebig and Doran 1999, Wander and Drinkwater 2000).

Concerns About the Soil Health Concept

Even though improving soil and water conservation through the soil quality concept is a goal for all land use stakeholders (Delgado and Cox 2003), soil health as a scientific field that

can be researched, is somewhat controversial. Soil is not directly consumed and so its qualities are judged according to external factors such as use, political climate, and environmental interactions (Doran and Parkin 1996). Some scientists believe that then placing an overall value judgment based on these external factors does not align with value-neutral science (Sojka and Upchurch 1999). They point out that quality is too contextual and has too many possibilities to be measureable (Cassel et al. 2003, Sojka and Upchuch 1999). A soil's function must be defined before it can be qualified. Its quality is in comparison to a desired level of functionality since there is no pure soil state (Gregorich et al. 1994). Soil functional goals range substantially, from sustainability of soil use, to producing quality food and fiber, providing ecosystem services, or its uniqueness (Warkentin 1995) and sometimes those functions are competing. In one context a soil may be functioning well, but in another context, that same soil may be functioning poorly and these two contexts may exist simultaneously (e.g. environmental remediation and crop production) (Cassel et al. 2003). There are no soil health indices that consider production, sustainability, and environmental consequences all at the same time and choosing which indices to use may be overly influenced by popular trends and assumptions in science (Sojka and Upchurch 1999). The concept of soil quality is important because it can be used to help the general public understand the value of soil (Karlen et al. 2003). On the other hand, the general public may not understand the nuances and potential flaws of soil health tests and results may be misinterpreted (Sojka and Upchurch 1999). Some soil scientists are concerned that the challenges associated with developing a soil health test reduce the scientific rigor of the concept, which may become no more than a fad (Cassel et al. 2003).

This controversy is healthy and is what ultimately pushes knowledge forward (Delgado and Cox 2003). It is important to carefully understand the importance of both sides without

polarizing legitimate concerns. It is also important to continue with research and not let disagreements stand in the way of the ultimate common goal. As stated by Sojka and Upchurch (1999), "Our children and grandchildren of 2030 will not care whether we crafted our definitions or diagnostics well. They will care if they are well fed, whether there are still woods to walk in and streams to splash in." It is simply how to get to this goal that is debated.

The Goals of Soil Health Research

The goal of a soil health test is to take into consideration: sustainability, environmental quality, and plant, animal, and human health. A successful soil health test would therefore be a primary indicator of sustainable land management (Doran and Zeiss 2000). Ideally, a "healthy" agricultural soil would increase agricultural sustainability by both increasing yield, and decreasing the amount of external inputs needed to produce that yield. It would accomplish this by being able to handle external stresses even with decreased inputs. A healthy soil should more efficiently cycle nutrients through the soil ecosystem and decrease use of external fertilizers (Gregorich et al. 1994).

A healthy soil should also decrease the environmental impacts of food production. Agriculture is a leading source of non-point source pollution in rivers and oceans (National Research Council 1993, Puckett 1995, Ritter 1988). Excess sediment, nutrients, pesticides, salts, and pathogens enter waterways through erosion, runoff, and leaching (Ribaudo et al. 1999). Sediment fills reservoirs, clogs waterways, increases the cost of water treatment, and degrades benthic habitat (Ribaudo et al. 1999, Ritter 1988). Eutrophication, which causes large dead zones of oxygen free water, is caused by algal blooms, which are fed by excess nitrogen and phosphorous (Ribaudo et al. 1999). A healthy soil could have improved soil structure, greater

water holding capacity, and higher cation exchange capacity, which would decrease nutrient runoff through decreased erosion and increased water infiltration. However, whether these goals are accomplished with a "healthier" soil completely depends on which soil indicator tests are chosen and how they are valued. Different stakeholders will have different needs and values, so soil health is not a concept that means the same thing to everyone.

Measuring Soil Health

The process of choosing and valuing soil health indicator tests is the crux of the soil health controversy. As has been pointed out, the goals of a healthy soil are complex and variable, there is no one laboratory "soil health" test or one "healthy soil" index. Instead the desired soil health goals must be defined by the stakeholder, broken into individual parts, those parts must be tested and valued, and then all the values can be combined into a final soil health score. Larson and Pierce (1991) have used the analogy of a physical to explain a soil health test. A doctor measures human indicators such as temperature, blood pressure, and weight in order to assess your overall health, just as a soil health test examines specific soil indicators to assess its functionality. The analogy can break down at the point of determining what function the soil is supposed to fill, but assuming clear goals have been defined, the assessment process is similar. To visualize the procedure of testing soil health by having a soil health goal, choosing appropriate indicator tests, scoring, and then combining those scores, Karlen et al. (2003) created the flow chart in Figure 1.2. The indicators selected to measure the performance of a desired soil function may be different for different soil health goals. Choosing these indicators of functionality is critical in creating a soil health test where the score is related to the goal (Larson and Pierce 1991).

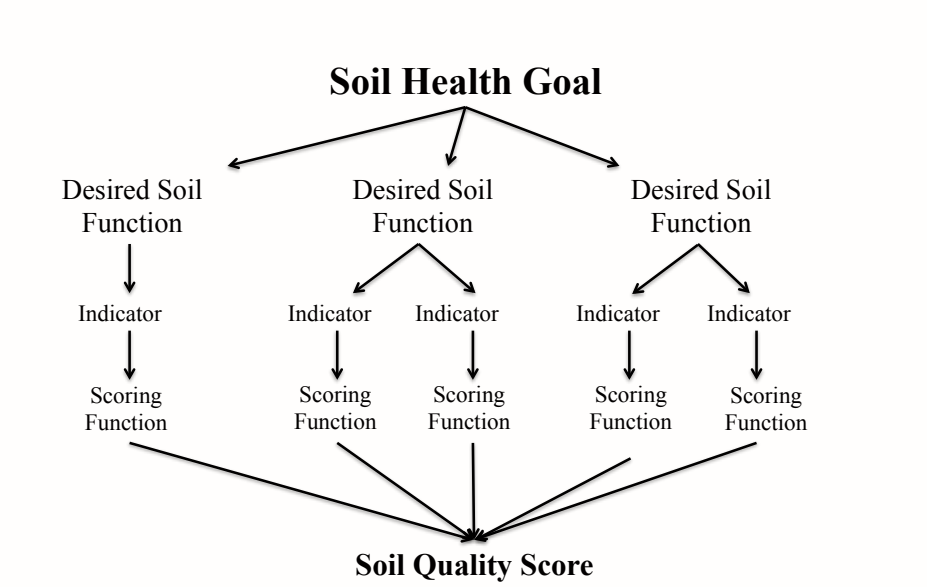

Figure 1.2 Visual depiction of the process to create a soil health test.

Once indicator tests are chosen, their values must be scored. Values are scored based on the desired amount of the indicator test. For example, to increase infiltration, more aggregation is desired, so if aggregate stability were the indicator test, the higher the amount of aggregation,

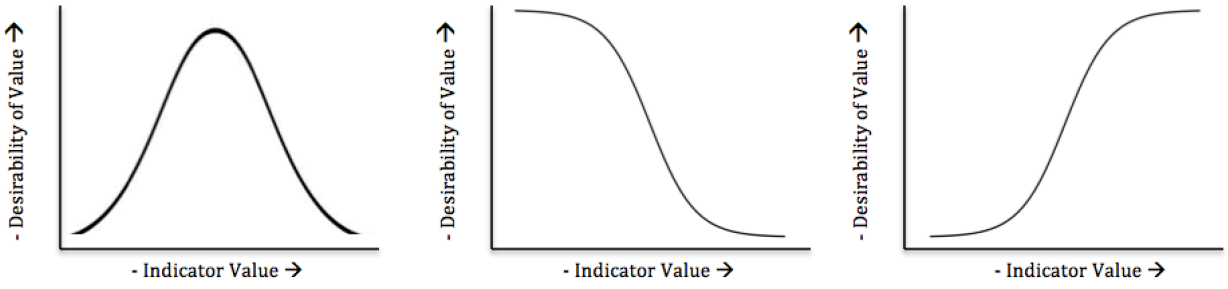

Figure 1.3 Soil health scoring curves representing three types of indicator value optimums. From left to right: specific desired range, less is better, and more is better.

the higher the score. On the other hand, heavy metal content can contaminate food, so the higher the heavy metal content, the lower the score. Figure 1.3 represents three common indicator scoring functions: more is better, less is better, or a specific range is desirable. A scoring function is assigned to each indicator test and used to give the test value a score. Since soil goals, indicator tests, and corresponding scoring functions are all chosen by the stakeholder, soil health tests reflect a society's current values (Andrews et al. 2004).

Agricultural soil health indicators must test the biological, chemical, and physical properties of soil, which support growth while maintaining environmental quality (Doran and Parkin 1996, Jackson et al. 2003, Karlen et al. 2003). Those indicators must reliably respond to management practices, indicate the condition of beneficial soil functions, demonstrate whether desirable functions are present or not, be fast, simple, and affordable (Doran and Zeiss 2000, Kennedy and Papendick 1995, Sarrantonio et al. 1996). Soil health indicator tests will become most useful if they can be performed, interpreted, and afforded by growers themselves (Sarrantonio et al. 1996). The best soil quality indicators are very sensitive to changing soil functionality (Andrews et al. 2004). Changes in soil management practices are often slow to show up in soil tests since the amount of bulk soil can be vast compared to the management practice (Warkentin 1995). It can be challenging to find soil tests that react before yield is affected due to the soil's ability to buffer the effects of soil management practices.

In order for soil health indicators to be adopted by growers, the soil must help to increase productivity and profitability of a farm. If profitability is not taken into consideration during soil health test development, then the tests will be assuming that growers are willing to subsidize the cost of soil sustainability, which is not realistic (Wander and Drinkwater 2000). Therefore economic sustainability of the land management practices is just as critical to a healthy soil as

environmental sustainability (Doran 2002). However, if profitability and productivity are the only goals of soil health, then soil quality tests will simply become soil productivity tests (Wander and Drinkwater 2000). A partial list of common soil health indicators can be found in Table 1.1. Some researchers have suggested using a large list of indicators, such as the one below, and a survey that selects indicators specifically for a soil use and location (Andrews et al. 2004).

Each step of measuring soil health has a point where the stakeholder must make a judgment: defining the soil goal, determining the desired soil functions that will accomplish that goal, choosing the correct indicator tests to measure the functions, and valuing the indicator test results. Many researchers are uncomfortable dealing with value judgments because it becomes difficult to remain objective.

Table 1.1 Commonly suggested soil health indicator tests beyond typical soil chemical analyses.

Indicator	Reference	Indicator	Reference
Soil Organic Matter	Andrews et al. (2002)	**Aggregate Stability**	Arshad and Martin (2002), Harris et al. (1996)
Total Organic C and N	Andrews et al. (2002), Gregorich et al. 1994, Weil et al. (2003)	**Bulk Density**	Doran and Parkin (1994), Larson and Pierce (1991)
Mineralizable C and N	Gregorich et al. (1994)	**Soluble Phosphorous**	Andrews et al. (2002)
Potentially Mineralizable Nitrogen	Doran and Parkin (1994)	**Test Phosphorus**	Harris et al. (1996)
Particulate Organic Matter	Wander and Bidart (2000)	**Cation Exchange Capacity**	Saviozzi et al. (1999)
Light Fraction Organic Matter	Gregorich et al. (1994), Janzen et al. (1992), Saviozzi et al. (1999)	**Soil pH**	Doran and Parkin (1994)
Active Carbon	Weil et al. (2003)	**Exchangeable Calcium**	Andrews et al. (2002)
Soil Carbohydrates and Phenolics	Saviozzi et al. (1999)	**Sodium**	Andrews et al. (2002)
Microbial Biomass	Gregorich et al. (1994)	**Electrical Conductivity**	Arshad et al. (2002), Smith and Doran (1996)
Hydrolytic and Urease Activities	Saviozzi et al. (1999)	**Soil Adsorption Ratio**	Andrews et al. (2002)
Carbohydrates	Gregorich et al. (1994)	**Zinc**	Andrews et al. (2002)
Enzymes	Gregorich et al. (1994)	**Heavy metal content**	Saviozzi et al. (1999)
Nematode Maturity Index	Bongers (1990)	**Available Water Capacity**	Larson and Pierce (1991), Lowery et al. (1996)
Metabolic Quotient	Gregorich et al. (1994)	**Soil Depth**	Arshad and Martin (2002)

THE STRAWBERRY

The strawberry, *Fragaria* X *ananassa*, is a broad-leaf perennial plant grown for its sweet ovary receptacle that is enjoyed as a fruit worldwide. A total of 4,594,540 metric tons were produced in 2011 (Boriss et al. web) and in the United States, which is the largest producer, the crop was worth $2,391,406 thousand (Perez and Plattner 2014). *Fragaria* X *ananassa* is a cross between two American wild octoploid strawberry species: *Fragaria virginiana* from the East coast and *Fragaria chiloensis* from the West coast. Both species were brought to Europe separately and were crossed in France in the 1750s.

Recommended Soil Properties for Strawberry Production

Specific soil recommendations for strawberry production have been established, although they vary based on region, variety, and production method. Soil pH is crucial for strawberry growth since nutrients are only available to plants within specific pH ranges. Pritts (2015) advises a pH between 6.0 and 6.8 for perennial strawberry production in the Northeast. However, in a survey of 53 commercial strawberry fields in CA, soils ranged in pH from 5.9-7.5 (Bottoms et al. 2013). The recommended pH level of strawberry production soil in Finland falls lower than the range recommended in the Northeast: 5.7-6.1 (Niskanen and Dris 2002). Another study found that strawberries grown in soil of about pH 6.7 had lower Fusarium wilt severity than strawberries grown in more acidic soils (Fang et al. 2012).

In the survey of strawberry farms in CA, texture ranged from 26% - 95% sand, 1% - 45% silt, and 4% - 47% clay (Bottoms et al. 2013). In Brazil researchers observed that many soil physical characteristics in strawberry fields changed with time including total porosity, macroporosity, bulk density, and available water capacity (Bamberg et al. 2011). They noticed

that available water capacity of tilled soils often returned to the pre-tillage state and therefore growers should determine their field's available water capacity before tilling (Bamberg et al. 2011). Pritts et al. (2015) found that yield was reduced and incidences of root disease increased in compacted soil.

Although soil chemical characteristics can be tested and normal nutrient ranges of productive fields have been calculated (Bottoms et al. 2013, Niskanen and Dris 2002), foliar nutrient assessments can give a more accurate picture of plant nutrient status. Foliar tests show how much of each nutrient is in the plant rather than in the soil, which may or may not be in a plant-available form. Foliar analysis can detect problems in nutrient levels before there is any economic loss, and foliar analysis gives a more comprehensive picture of micronutrient and N status than soil sampling (Pritts 2015). Therefore, growers determine their plant available nutrient status by collecting leaf samples and analyzing leaf nutrient status. Even leaf nutrient ranges are variable because plant need depends on geographical location, soil type, soil structure, production system, plant growth stage, and year (Bottoms et al. 2013). In the hot semiarid regions of Spain and California, target leaf nutrient ranges were similar to each other, but different from leaf nutrient ranges in cold Finland, or humid Florida (Bottoms et al. 2013).

Soil type, plant variety, and management practices in strawberry fields have all been shown to affect soil microbial growth. For example, strawberries are known to form relationships with arbuscular mycorrhizal fungi, which help roots uptake nutrients, especially phosphorous. One study found different strawberry varieties formed relationships with different fungal strains, and these relationships did not necessarily increase plant growth (L et al. 2007). However, a different study found that in two different fields and four different cultivars, arbuscular mycorrhizal fungi strains differed with soil type but not strawberry variety (Santos-

Gonzalez et al. 2011). Strawberry field management also affects soil biological composition. Soils amended with manure compost or pea straw crop residue had lower strawberry Fusarium wilt severity at 5% compost residue additions than without additions (Fang et al. 2012). In other fields amended with vermicomposts, total soil nutrient content remained the same as inorganic-fertilized plots, but soil microbial growth increased (Arancon et al. 2006). Organically managed day-neutral strawberries in California had more C, N, microbial biomass, and functional gene abundance and diversity than their conventionally managed counterparts. These differences were probably due to soil fumigant and synthetic pesticide use in conventional fields, and increased compost addition rates in organically managed fields (Reganold et al. 2010).

The field of *soil health* attempts to measure these physical, chemical, and biological components of soil and qualify them in terms of negative environmental impacts as well as soil productivity. To date, very little research has been done applying soil health tests to strawberry production. Pritts et al. (2014) surveyed matted row strawberry fields across NY using the Cornell Soil Health Test, and concluded that soil chemical and physical soil health indicators were generally within acceptable ranges according to their indicator tests, but soil biological health indicators were below desired ranges.

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CHAPTER 2

THE EFFECTS OF TILLAGE DEPTH AND SOIL AMENDMENTS ON STANDARD SOIL HEALTH INDICATOR TESTS AND STRAWBERRY PLANT GROWTH

ABSTRACT

When seven matted row strawberry fields across New York State were given Cornell Soil Health Tests in 2012, the biological components of the soil test were consistently low. The hypothesis was that the C:N ratio of soil amendments and deep or shallow tilling would affect soil biological health indicator tests, creating a range of soil health scores that could be used to predict plant performance. Pre-plant soil amendments along a C:N ratio scale (grass, straw, sawdust, or unamended soil) were applied to a field in fall 2013 prior to planting strawberries in spring, and again in fall 2014. The planting was tilled deep or shallowly for the 2014 and 2015 growing seasons. Soil samples were taken in May, June, and September 2014 and May and August 2015. Potentially mineralizable nitrogen (PMN), soil respiration, bulk density, C:N ratio, pH, and soil moisture, was tested. Strawberry yield data were collected in June 2015. There was a consistent pattern of sawdust-amended plots having the highest respiration and PMN rates in the spring, probably from increased microbial activity ($p < 0.05$). By the third sample date pH was higher between the rows than within the rows and bulk density varied based on soil amendment and sampling between or within the rows, suggesting that sample time, location, and method all affect soil health indicator results. The C:N ratio and soil moisture remained unchanged. Yield and plant density were lower in straw-amended plots; however, there was no correlation between yield and soil health variables.

INTRODUCTION AND HYPOTHESES

Soil Amendments

Studies show the importance of adding organic amendments to soil to increase crop yield and improve many common soil health indicator tests. Compared with bare soil, mulch can significantly increase microbial biomass N and C, soil extractable N, net N mineralization, and soil microbial respiration (Tu et al. 2006). Some key characteristics that affect an amendment's interaction with soil biological health indicators are: N content, lignin, water soluble N, cellulose, phenolic acids, and C:N ratio (Bengtsson et al. 2003, Frankenberger and Abdelmagid 1985, Martens 2000). Although all these characteristics affect organic matter decomposition in soil, the C:N ratio is especially important. Nicolardot et al. (2001) found that the C:N ratio of the soil amendment could be used in a simplified model to predict residue decomposition since the other characteristics were either constant or related to the C:N ratio. Manzoni et al. (2010) also found that in their study stoichiometric relationships were more important than other amendment chemical qualities. Since soil microbes metabolize C and N at a rate of about 24:1, high C:N ratio mulch additions can lead to N immobilization (Manzoni et al. 2010, Schonbeck and Evanylo 1998). When an amendment with a C:N ratio higher than 24:1 is added to the soil, microbes must find outside sources of N to continue metabolizing the C source, reserving soluble soil N in the microbe but making it unavailable to plants. In a study by Trinsoutrout et al. (2000) crop residues with a C:N ratio between 24 and 150 led to net N immobilization after 168 days, but residues with a C:N ratio between 10 and 24 led to net N mineralization over the same time period. Brooks et al. (1985) found that chloroform fumigated soils release increasing amounts of N with increased fumigation times, supporting the idea that soil microbes retain N in their cells until it is released into the soil as they die. In another study, researchers found that higher

amounts of organic C added to the soil increased microbially mediated N immobilization (Congreves et al. 2012). Schonbeck and Evanylo (1998) specified that organic material with less than 15-17 g N kg^{-1} dry weight immobilized soluble N. However, high C:N ratio amendments do not always lead to N immobilization. In a study by Malhi et al. (2011) they recognized that although high C:N ratio amendments likely immobilized N, the effect was not great enough to affect the yield of organic-mulched tomato crops. Similarly, Schonbech and Evanylo (1998) observed that annual applications of straw containing less than 10 g N kg^{-1} dry weight enhanced soluble N in the long run.

Tilling

Soil cultivation also affects soil quality, and in some instances more so than residue management (Blanco-Canqui and Lal 2007). Worm counts, which can be used as a soil health indicator test, increased faster under reduced till systems than in conventional till systems (Braunack et al. 2012). Soil microbial diversity, both species richness and evenness, is lower in conventionally tilled fields than in reduced tillage fields (Lupwayi et al. 1998). Soil fungi are more affected by tilling than soil bacteria and fungal biomass is lower in tilled systems than untilled (Beare et al. 1997, Frey et al. 1999). No tilling systems have been shown to increase populations of the disease-suppressive microorganisms: actinomycetes, *Trichoderma* spp., and *Gliocladium* spp. (Vargas et al. 2009). Tilling can also affect crop yield. In some cases reduced tillage increases yield, such as with some varieties of carrots (Brainard and Noyes 2012), zucchini (Canali et al. 2013), and pumpkin (Rapp et al. 2013). However, results are variable based on crop, variety and growing conditions (Brainard and Noyes 2012). Reduced tillage does

not always affect yield (Braunack et al. 2012, Rapp et al. 2004, Vakali et al. 2014) and in some instances it can even decrease yield (Vakali et al. 2014).

There are a variety of ways tilling affects the soil biology and therefore yield. Soil health decreases as tilling increases runoff, decreases macro- and micro-porosity, and forms plough pans (Roth et al. 1988). Tilling, especially tilling cover crop residue into the soil, exposes more weed seeds to light and therefore can increase weed pressure (Canali et al. 2013, Rapp et al. 2004). In no till systems macroaggregate turnover is slow. When this process is slow, it allows time for microaggregates to form inside the macroaggregates, and within these microaggregates, C is stored (Six et al. 2000). Tilling breaks up these pockets of soil organic matter so they are exposed to oxygen and mineralized (Jackson et al. 2003), which causes soil organic matter loss over time (Holland and Coleman 1987). Soil organic matter mineralization causes a burst of available soil N, making cultivation an attractive process, but in the short term only because organic N sources are depleted as they are mineralized (Jackson et al. 2003). Available nutrients are easily leached after a tilling event because soil microbes are not able to assimilate nutrients as effectively (Jackson et al. 2003). Switching to a reduced-till system can increase soil organic matter in the long run as it is better protected against mineralization and leaching (Wander and Bidart 2000). Many long-term studies find higher soil organic C levels in reduced till systems, especially in the upper levels of the soil horizon (Bayer et al. 2001, Gal et al. 2007, Jarecki and Lal 2005, West and Post 2002).

Not all studies have found reduced soil organic C levels in conventionally tilled systems compared to reduced tillage (Baker et al. 2007, Jarecki and Lal 2005). Often, depth of sampling is cited as a reason why some studies find increased soil organic matter in reduced tillage treatments while others do not. Soil organic C may be lower in the soil profile in conventionally

tilled fields. C from surface organic matter stays at the top of the soil horizon in reduced tillage systems, but in conventional tillage it is mixed deep into the profile. Roots are another significant source of soil organic carbon and rooting depth is deeper in conventionally tilled fields (Baker et al. 2007). However, in a strawberry system, where the root zone is relatively shallow, reduced tillage may increase soil biological health indicator test scores and yield.

Interaction

Tilling mulch into the soil mixes the soil and organic matter together, making it more accessible to microorganisms in the soil, and more easily broken down than if the mulch were left on the surface of the soil (Blanco-Canqui and Lal 2007, Christensen 1986, Holland and Coleman 1987). This leads to faster litter decomposition in tilled systems than untilled systems (Holland and Coleman 1987). This is supported in a study by Haramoto and Brainard (2012), where inorganic nitrogen levels spiked earlier in the season in fields with cover crop residue tilled into the ground. They believe that the residue incorporation caused faster decomposition, while the residue in strip tilled plots stayed primarily on the soil surface and therefore its decomposition was more variable. Tilling amendments into the soil also affects the location of nutrients in the soil profile. In a study by Vakali et al. (2014) nitrate levels and depth within the soil profile varied based on tilling method, although these variations were not consistent with each type of crop residue.

Hypotheses

The hypotheses in this study were that the C:N ratio of soil amendments and tillage depth would affect soil biological health indicators and strawberry yield. The prediction was that

higher C:N ratio amendments would increase soil microbial life and therefore soil respiration and the soil C:N ratio, but they may immobilize N and therefore yield and N mineralization may be compromised. Lower C:N ratio amendments may increase N availability, N mineralization, and therefore yield, but keep respiration constant. Higher respiration and N mineralization was expected early in the season in deep tilled treatments than in shallow tilled, but that trend was expected to flip later in the season. Another hypothesis was that yield would be correlated with some soil health indicator tests. If soil health indicator tests were combined using a Principal Component Analysis (PCA) it was expected that the first component could be called "soil health" and would be positively correlated with yield. This correlation was expected to become stronger with time, especially as soil amendments with a high C:N ratio begin to mineralize instead of immobilize N.

MATERIALS AND METHODS

Site

These hypotheses were tested at a research farm in Ithaca, NY. The GPS coordinates for the field were: 42°26'30" N and -76°28'19" W. The hardiness zone was 6a and the predominant soil type was Arkport fine sandy loam. The mean annual temperature from 1981-2010 was 8.1°C and the mean annual precipitation was 78.9 mm.

Field Set-Up

A completely randomized 2 x 4 factorial plot design was laid out with each of the 8 treatments replicated 4 times. The plots were 3.7 x 4.6 m and the entire plot received the soil amendment. Each plot contained two border rows and two rows from which data were collected.

To minimize the size of the experimental area, border rows in any one plot served as borders for adjacent plots. The experimental design is diagramed in Figure 2.1. Grass, straw, and sawdust were used as soil amendments as well as a control plot without any soil amendments.

Table 2.1 Total C, total N, and mean C:N ratio of soil amendments applied to the strawberry field in East Ithaca, NY (n=3)

Amendment	Dry Mass Added (Kg)	Total C (Kg)	Total N (Kg)	Mean C:N Ratio	SE
Sawdust	14.5	14.5	0.04	344	16
Straw	14.5	14.4	0.15	93	5
Grass	14.5	13.8	0.73	19	2

In Fall 2013, 14.5 kg dry weight of each amendment was spread uniformly in the plots and incorporated. This rate corresponds to a typical straw mulch application rate for winter protection (approximately 9 metric tons per hectare). On 6 May 2014 bare root 'Honeoye' strawberries (*Fragaria* X *annanasa*) from Nourse Farms, MA, were planted. Spacing was 0.18 m within-row and 1.2 m between-rows. Grass-, straw-, sawdust-, and unamended treatments were either shallow-tilled or deep-tilled for weed control throughout the life of the planting. Shallow-tilled plots were cultivated with a Reigi-weeder rotary cultivator until the strawberry planting became too dense, then a rototiller was used at the shallowest setting. Shallow-tilled plots were only tilled to about 80 mm and deep-tilled plots to about 0.30 m. When the rotary cultivator was used for the shallow plots, it also weeded the deep till plots before the rototiller was used. Any remaining weeds were pulled by hand and incorporated into the soil at regular intervals. Soil amendments were spread again at the same rate per plot in fall 2014, but only between the rows. The field was protected with two layers of 1.5 oz spunbonded polypropylene row cover (DeWitt Supreme Frost Blanket) during the winter to prevent cold damage.

S1	C2	D1	C1	Blank	C2
D2	S2	G2	G2	D2	S1
S1	D2	C2	G1	C1	G1
Blank	S2	Blank	S2	D1	S2
D1	G1	S1	C2	Blank	G2
G2	D1	C1	D2	C1	G1

Legend			
Unamended	C	Deep Till	1
Grass	G	Shallow Till	2
Straw	S		
Sawdust	D		

Figure 2.1 Plot map of treatments applied to the field in Ithaca, NY

Soil Collection

Soil samples were collected 1 May (before planting), 17 June, and 20 September 2014 then 19 May, and 18 August 2015. Any debris was brushed to the side and a soil probe was used to collect the top 0.15 m of soil. Within each plot eight cores were collected and aggregated into two different clean, plastic bags. Four of the cores were collected from between the strawberry rows and the other four were collected from within the strawberry rows. On 1 May the strawberries were not yet planted, so eight cores were collected and aggregated into one bag.

Between plots the probe was wiped clean with a gloved hand and "rinsed" with some soil from the next plot. After collection, each bag was placed immediately into a cooler with ice packs until it could be transported to the walk-in cooler. All soil samples were collected within one day.

After soil was collected it was stored in a walk-in cooler kept at 3°C. Before sieving, soil was mixed within the bag. Field moist soil was transported and stored in a portable cooler with ice packs to slow microbial activity when being processed. All the soil from a bag was sieved through a 4-mm sieve before sieving half the sample through a 2-mm sieve. Sieves were fully washed and dried between samples. All soil was sieved within 6 days of soil collection.

Bulk density samples were collected in September 2014 and October 2015 using 50 mm diameter x 50 mm length aluminum soil cores. Three cores were stacked, hammered into the ground and then excavated with a trowel without disturbing the core. A paint scraper cut off excess soil at the bottom of the core and split each core into its three 50 mm sections to record density differences across the top 0.15 m of soil. The sections were emptied into a paper bag and dried at 65°C for 1-2 weeks and weighed. Density was calculated as mass divided by volume. Bulk density was measured both within and between rows.

Measuring Soil Traits

After each bag was aggregated, before sieving, soil was removed for soil moisture. Between 20 and 30 g of soil was removed and placed on a torn metal plate. The total weight was recorded and then the plate was dried at 105°C for 24 hours. The dry weight was recorded and percent moisture was calculated by subtracting the soil moisture weight from the total soil weight.

Next, 8.00 ± 0.03 g of field moist soil sieved to 2 mm, was weighed into two acid washed 50 mL centrifuge tubes for Potentially Mineralizable Nitrogen (PMN) analysis (Gugino et al. 2009). One set of tubes had 40 mL of 2.0 M KCl added, tubes were shaken for 1 hour, and the solution was filtered through 0.15 m VWR 313 grade fluted filter paper. This filtrate was frozen until ready for analysis. The other set of tubes received 10 mL of deionized (DI) water. They were made anoxic by partially capping the tube with a rubber stopper and purging the headspace for 45 seconds with N gas before fully capping and sealing with electrical tape. These tubes were placed in an incubation room at 30°C for 7 days. When taken out of the incubation room, 30 mL of 2.67 M KCl was added to each tube to bring the solute to a total volume of 40 mL of 2.0 M KCl and treated the same as initial samples. The extracts were analyzed for ammonium N using the colorimetric method (Mulvaney 1996) using an automated analyzer (Bran+Luebbe Auto Analyzer 3, Digital Colorimeter, Cornell Nutrient Analysis Laboratory, Ithaca, NY).

Soil that had been sieved to 2 mm was air dried after PMN analysis and 10 g was weighed into a clean 50 mL centrifuge tube. Before shaking for 1 hour, 30 mL of DI water was added to each centrifuge tube. After shaking, a pH meter suspended in the solution was used to measure pH.

Soil respiration was measured using a method described by Whitman et al. (2014). About one week after sampling 10.00 ± 0.05 g of field moist soil sieved to 4 mm was weighed into acid washed glass Qorpak vials and then stored in the cooler for another week. Resting after the disturbance from sampling and sieving helped to measure more typical field respiration, not respiration after a disturbance. Thirteen days after sampling, the Qorpak vials were placed inside mason jars in an incubation room at 30°C. The mason jars had 5 mL of CO_2-free H_2O on the bottom and a scintillation vial with 15 mL of 0.09 M KOH next to the Qorpak vial. Water kept

the environment moist so the soil did not dry out. The KOH was trap for the CO_2 introduced to the system through respiration. The jars were sealed with a Mason jar lid. The electrical conductivity (EC) of the scintillation vial was measured at days 2, 4, 7, 13, and 20. The base EC of the KOH solution was measured once every 12 jars to get an average base EC and the change in base EC and final EC was used to calculate the rate of CO_2 added to the jar. Each time EC was measured, the CO_2-free water and the KOH in the jars were replaced and a new base EC was calculated. A standard curve was created using 6 mason jars with septum lids that contained KOH and CO_2-free water. Known volumes of pure CO_2 were injected into the jars through the septum lids and after 24 hours the change in EC was measured. The standard curve is shown in Figure 2.2.

Soil dried and sieved to 2 mm was ground to a powder using a ball mill and analyzed for C and N using a ConFlo III elemental analyzer (Cornell University Stable Isotope Laboratory, Ithaca, NY). C measured was organic C only as there were no carbonates in the soil. The soil was tested for carbonates using a modified Bernard Calcimeter method (Sherrod et al. 2002). About 0.50 g of soil was weighted into a clean gas sampler, which was then attached to a

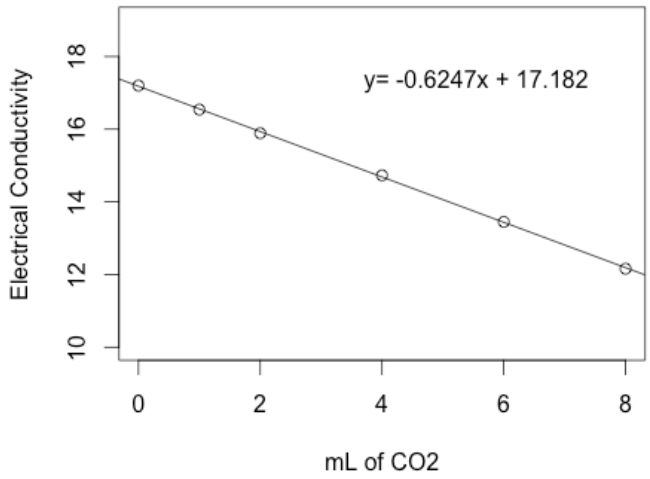

Figure 2.2 Standard curve of the Electrical Conductivity (EC) of 0.09 M KOH at corresponding volumes of CO_2

Bernard Calcimeter using a needle inserted into the septum lid. The water level in the pipet and the conical glass funnel were zeroed, and then 5 mL of 6 M HCl was added to the gas sampler. The water level in the pipette decreased in accordance with the acid added to the sampler and was re-zeroed with the glass funnel. Since no carbonates were present the water level remained zeroed.

Measuring Plant Traits

To check for nutrient deficiencies, strawberry leaves from each treatment were collected in August 2014. The leaves were the youngest fully formed leaves representative of leaves within the plot. Leaves were gently washed with DI water and dried in an oven at 70°C for 4 days. Dry leaves were first run through a Wiley mill and then ground to a powder in the ball mill. Once powdered, 0.50 g was weighed into a clean digestion tube. To each tube 5.0 mL of concentrated HNO_3 was added and left overnight. The next day the tubes were digested at 125°C for one hour then removed. Once cool, 3 mL of 30% H_2O_2 was added to each tube and the temperature of the digestion block was brought slowly up to 125°C again. H_2O_2 was added until the digest was colorless then each tube was digested to just dryness. Once a sample was dry it was removed and 10 mL of 1:10 concentrated HCl was added to the tube. Each sample was vortexed and filtered through 0.15 m VWR 313 grade fluted filter paper and analyzed by Inductively Coupled Plasma Spectrometry (Thermo iCAP 6500 Duo series ICP, Biological and Environmental Engineering Soil and Water Lab, Ithaca, NY) for nutrients. Powdered leaves were analyzed by dry combustion for total C and N analysis as described above.

Plant density was measured on 6 July 2015 by randomly placing two 0.25 m squares on the two non-border rows in each plot. All plant material within the squares was cut and dried at

55°C for 7 days. Once dry, the leaves were weighed and a subsample was ground using the Wiley Mill. Then leaves were ground into a powder using the ball mill at 30 rpm for 2 min 30 sec. Leaf powder was analyzed for nutrients, C, and N as described above.

Strawberry yield data were collected from 9 June through 25 June 2015. A 2 m section of each non-border row was marked for harvest for a total of 4 m of harvested row for each plot. At each harvest date all the strawberries from plants within that section of row were picked. Moldy and damaged fruit was kept separate from marketable fruit and weighed separately.

Statistical Analysis

R software was used for all statistical analyses (Version 0.98.495 © 2009-2013 RStudio, Inc.). All non-normal data was log transformed and results were considered significant if $p < 0.05$. For post-hoc comparisons Tukeys HSD tests were used to determine significant differences between treatments.

The first question to address was whether soil health indicator tests were affected by soil amendments, tillage depth, sample location (between or within rows), and their interactions. To look at this relationship linear mixed models were used, setting soil amendment, tillage depth, and sample location as fixed effects, and each unique plot as a random effect. On the first sample date strawberries had not been planted so there was no distinction between sampling between or within the rows and sample location was not included in the model.

The second question was whether treatments had an effect on yield. General linear models were used to analyze relationships between treatments and yield and correlations between soil health indicators and yield. Since many of the soil health indicator tests are interdependent and interact with one another a principal component analysis was run to check for

issues of co-linearity (Arshad and Martin 2002). If the majority of the soil health indicator tests had loaded into the same component, then that component would have been used as the independent variable instead of the individual soil health indicator tests.

RESULTS

Soil Health Indicator Tests

Soil Respiration

Somewhat consistently, soil amendments significantly affected the mg CO_2-C mg^{-1} soil-C from soil respiration. The interactions of soil amendment and sample location, and soil amendment and tillage depth sometimes affected soil respiration as well (Table 2.2). In May 2014 sawdust-amended soil had the highest respiration rates, but by June 2014 straw-amended soil had the highest respiration rates (Figure 2.3). In September 2014 straw-amended soil within the rows had higher respiration than straw-amended soil between the rows (Figure 2.3). In May 2015, again the interaction of soil amendment and sampling between or within the rows was significant: unamended soil within the rows had much higher respiration than unamended soil between the rows (Figure 2.3).

The greatest increases in soil respiration from unamended soil per kg of amendment-C were from sawdust (Figure 2.4).

Table 2.2 Effects of three treatments: soil amendments, tillage depth, sampling between or within rows, and their interactions on five soil variables: soil respiration, potentially mineralizable nitrogen (PMN), C:N ratio, soil moisture, and pH. At the first sample date, no strawberries had been planted, so there was no sample location treatment. $P < 0.05$ are significant and are reported below, all non-significant data are noted with an "ns." When necessary non-normal data was log transformed to satisfy the assumption of normality of residuals.

		Soil Health Indicator Tests				
Sample Date		**Respiration (mg CO_2-C g^{-1} soil-C)**	**PMN (mg N g^{-1} soil-N)**	**C:N**	**Soil Moisture (%)**	**pH**
5/1/14	Amendment	<0.0001	0.008	ns	0.05	ns
	Tillage Depth	ns	ns	ns	ns	ns
	Amendment: Tillage	ns	ns	ns	ns	ns
6/17/14	Amendment	<0.0001	ns	ns	ns	ns
	Tillage Depth	ns	ns	ns	ns	ns
	Sample Location	ns	ns	ns	ns	ns
	Amendment: Tillage	ns	ns	ns	ns	ns
	Amendment: Sample Location	ns	ns	ns	ns	ns
	Tillage: Sample Location	ns	ns	ns	ns	ns
9/24/14	Amendment	ns	ns	ns	ns	ns
	Tillage Depth	ns	ns	ns	ns	ns
	Sample Location	ns	ns	ns	<0.0001	<0.0001
	Amendment: Tillage	0.01	ns	0.02	ns	ns
	Amendment: Sample Location	0.04	ns	ns	ns	ns
	Tillage: Sample Location	ns	ns	ns	ns	ns
5/19/15	Amendment	<0.0001	0.01	ns	ns	ns
	Tillage Depth	ns	ns	ns	ns	ns
	Sample Location	ns	ns	ns	ns	0.0002
	Amendment: Tillage	ns	ns	ns	ns	ns
	Amendment: Sample Location	0.03	ns	ns	0.02	ns
	Tillage: Sample Location	ns	ns	ns	ns	ns
8/19/15	Amendment	ns	ns	ns	0.002	ns
	Tillage Depth	ns	ns	ns	ns	ns
	Sample Location	ns	0.01	ns	<0.0001	<0.0001
	Amendment: Tillage	ns	ns	ns	ns	ns
	Amendment: Sample Location	ns	ns	ns	ns	ns
	Tillage: Sample Location	ns	ns	ns	ns	ns

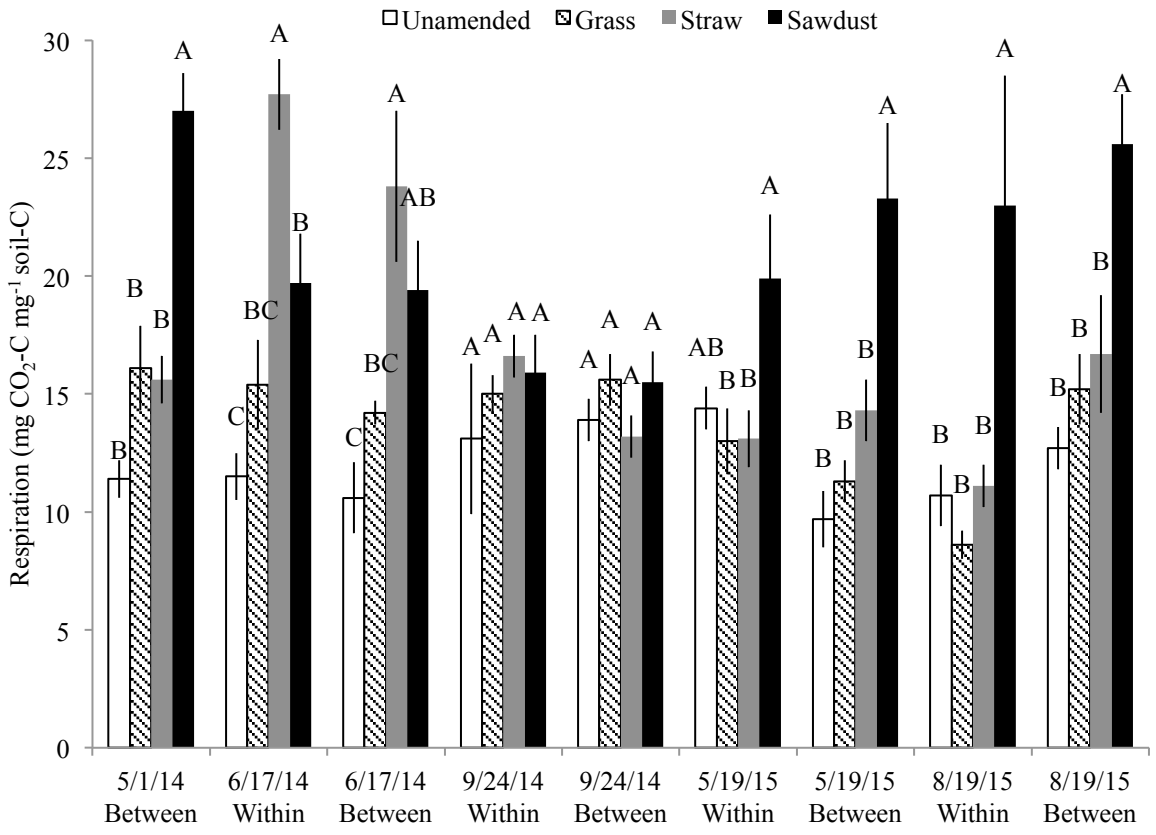

Figure 2.3 Mean total soil respiration based on soil amendment. Error bars are standard errors. Bars labeled with different letters are significantly different from other bars within the cluster based on a Tukey's HSD test ($p < 0.05$).

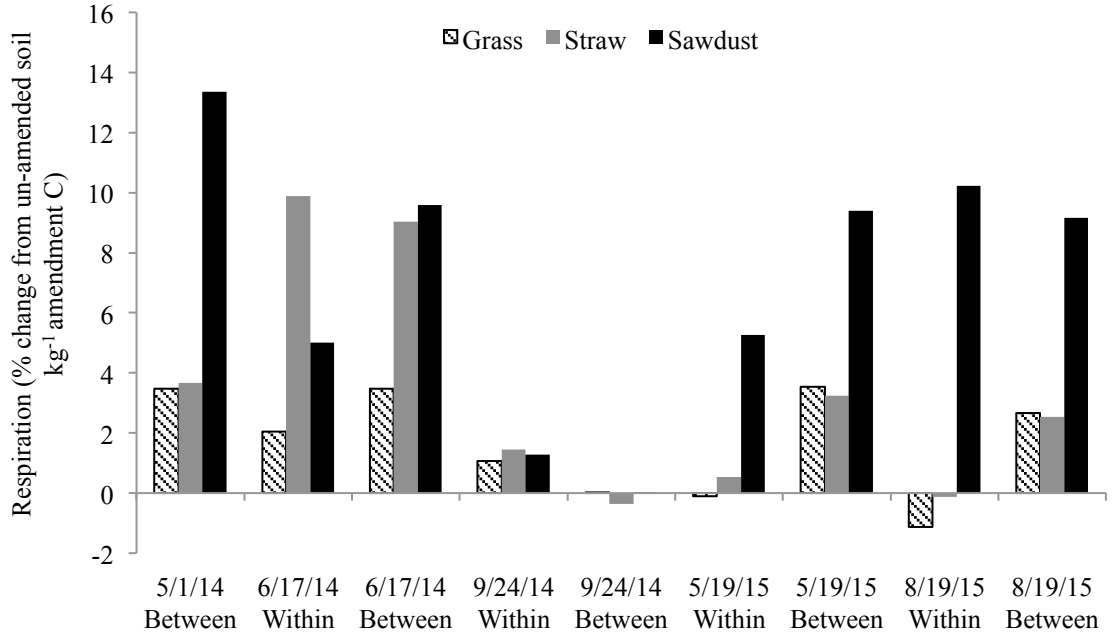

Figure 2.4 Mean percent change in respiration from unamended soil per kg of amendment-N by soil amendment.

Potentially Mineralizable Nitrogen

PMN was affected by soil amendment each spring and by sampling between or within the rows in August 2015 (Table 2.2). In May 2014 NH_4^+ mineralization was highest in sawdust-amended soil and in May 2015 unamended soil had lower NH_4^+ mineralization than straw-amended soil. In August 2015 N mineralization was higher within the rows than between the rows (Figure 2.5).

The greatest increases in N mineralization from unamended soil per kg of amendment-N were from sawdust (Figure 2.6).

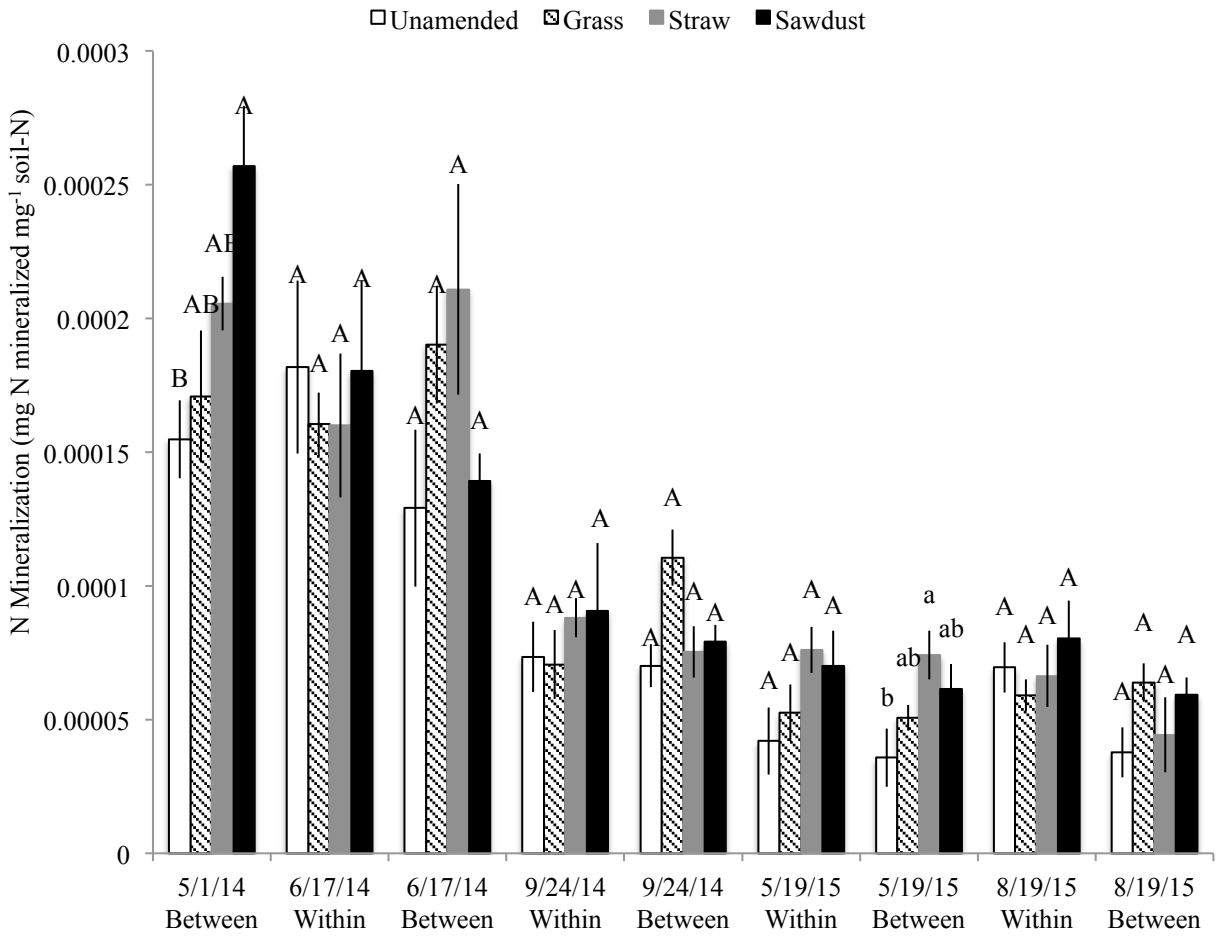

Figure 2.5 Mean soil PMN based on soil amendment. Error bars are standard errors. Bars labeled with different capital letters are significantly different from other bars within the cluster based on a Tukey's HSD test ($p < 0.05$). Bars labeled with diffe

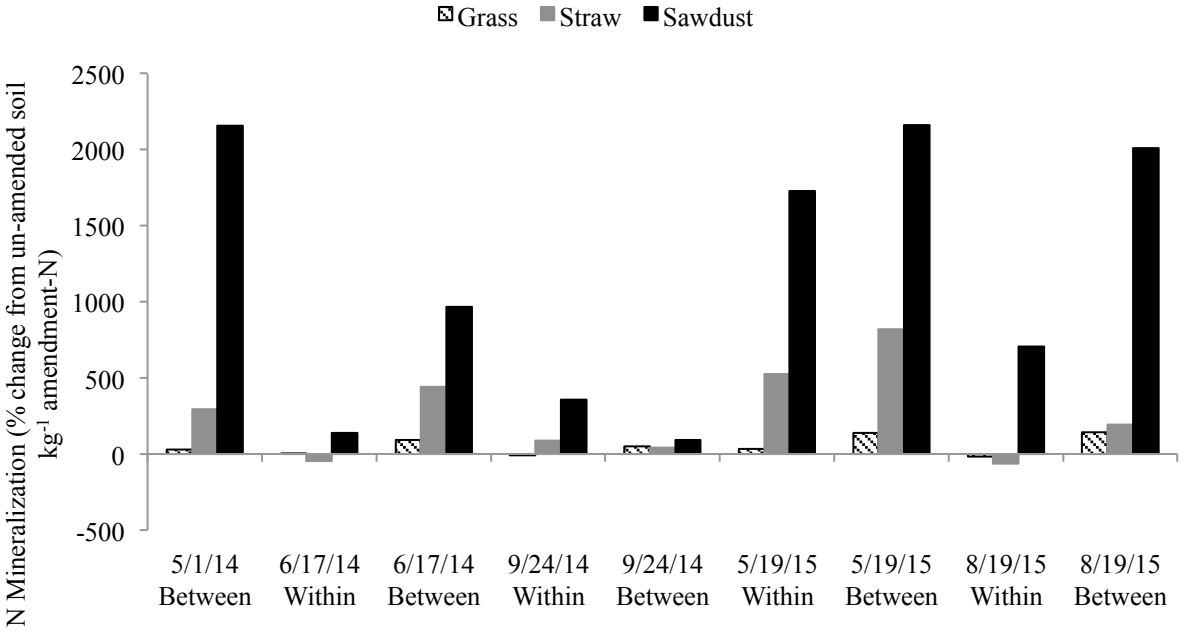

Figure 2.6 Mean percent change in PMN from unamended soil per kg of amendment-N by soil amendment.

C:N Ratio, Soil Moisture, pH

The C:N ratio of the soil was only affected by the interaction between soil amendment and tillage depth in September 2014 but this was not a consistent trend (Table 2.2). Similarly, soil moisture was affected by some treatments, but without a discernable pattern (Table 2.2). On the other hand, pH was the same across treatments (Table 2.2), but from September 2014 on, average pH was higher between the rows and lower within the rows (Figure 2.7).

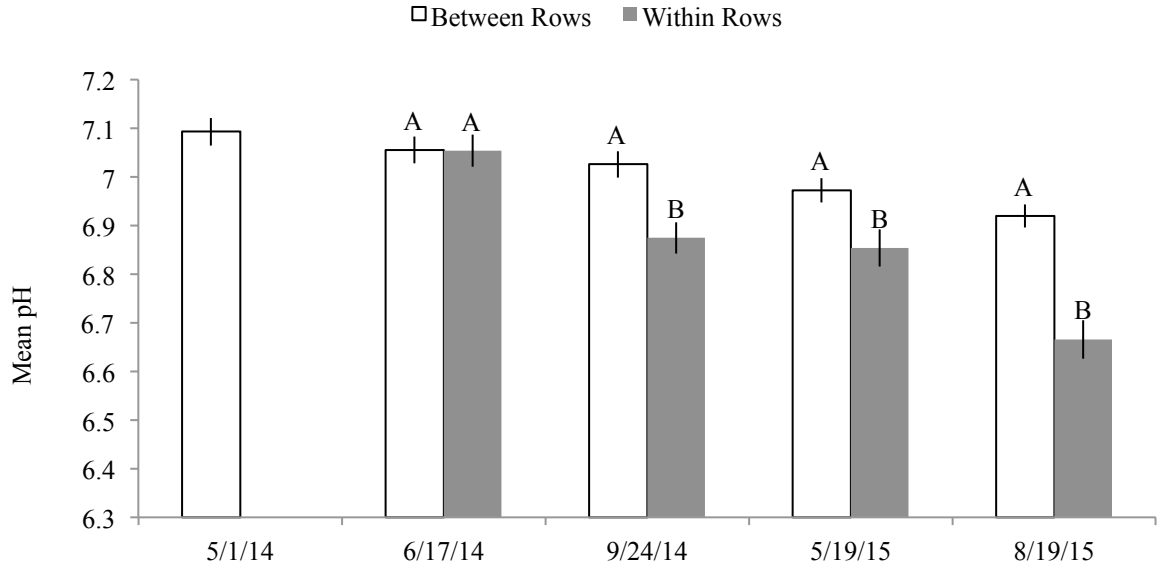

Figure 2.7 Mean soil pH between the rows and within the rows. Error bars are standard errors. Bars labeled with different letters are significantly different from the other bar in the cluster based on a Tukey's HSD test ($p < 0.05$).

Bulk Density

In 2014 bulk density was affected by an interaction between soil amendment and sample depth, an interaction between tillage depth and sample depth, sampling between or within the rows, and sample depth (Table 2.3). In 2015 bulk density was affected by an interaction between soil amendment and sampling between or within the rows, as well as sample depth and soil amendment (Table 2.3).

In 2014 bulk density was higher in shallow tilled plots in the top 0.10 m of soil, but that difference disappeared lower in the soil profile (Figure 2.8). Straw-amended soil in the top 0.05 m of the soil profile was less dense than all other soil amendments, but again the difference disappeared lower in the soil profile (Figure 2.9).

In 2015 the density was the same between and within the rows except for straw-amended plots, where the density was higher within the rows than between (Figure 2.10). Building on trends from 2014, the soil was more dense deeper in the soil profile (Figure 2.11).

Table 2.3 Treatment effects on bulk density in 2014 and 2015. $P < 0.05$ are significant and are reported below, all non-significant data are noted with an "ns." When necessary non-normal data was log transformed to satisfy the assumption of normality of residuals.

	Bulk Density	
Year	**Factor**	***p***
2014	Amendment	ns
	Tillage Depth	ns
	Sample Depth	<0.0001
	Sample Location	0.002
	Amendment: Sample Location	ns
	Sample Depth: Tillage Depth	0.03
	Amendment: Sample Depth	0.004
	Amendment: Tillage Depth	ns
2015	Amendment	0.01
	Tillage Depth	ns
	Sample Depth	<0.0001
	Sample Location	ns
	Amendment: Sample Location	0.03
	Sample Depth: Tillage Depth	ns
	Amendment: Sample Depth	ns
	Amendment: Tillage Depth	ns

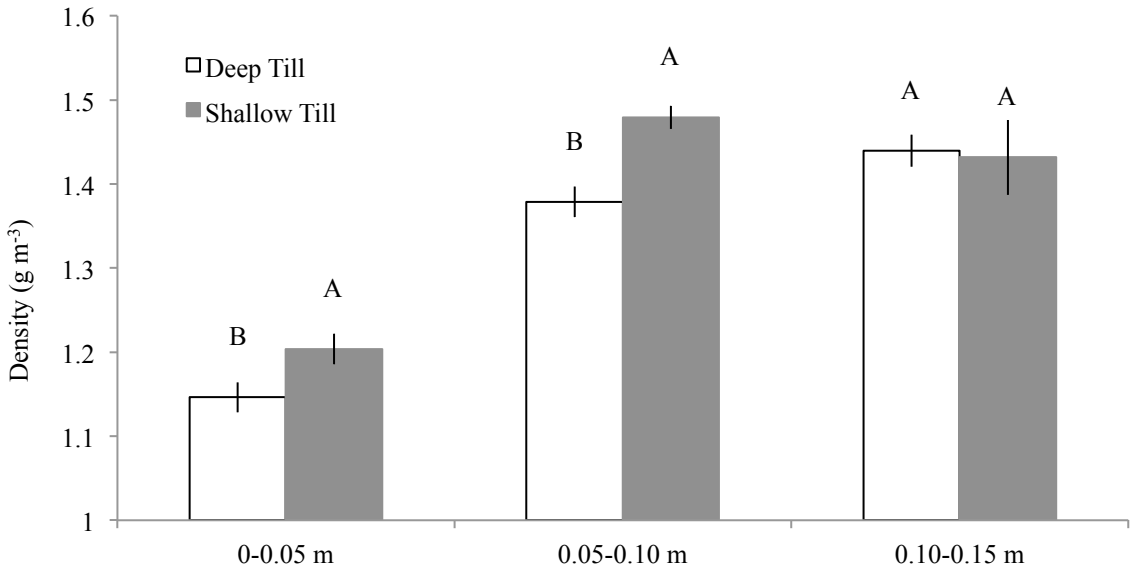

Figure 2.8 Mean soil bulk density based on tillage depth in 2014. Error bars are standard errors. Bars labeled with different letters are significantly different from the other bar within the cluster based on a Tukey's HSD test ($p < 0.05$).

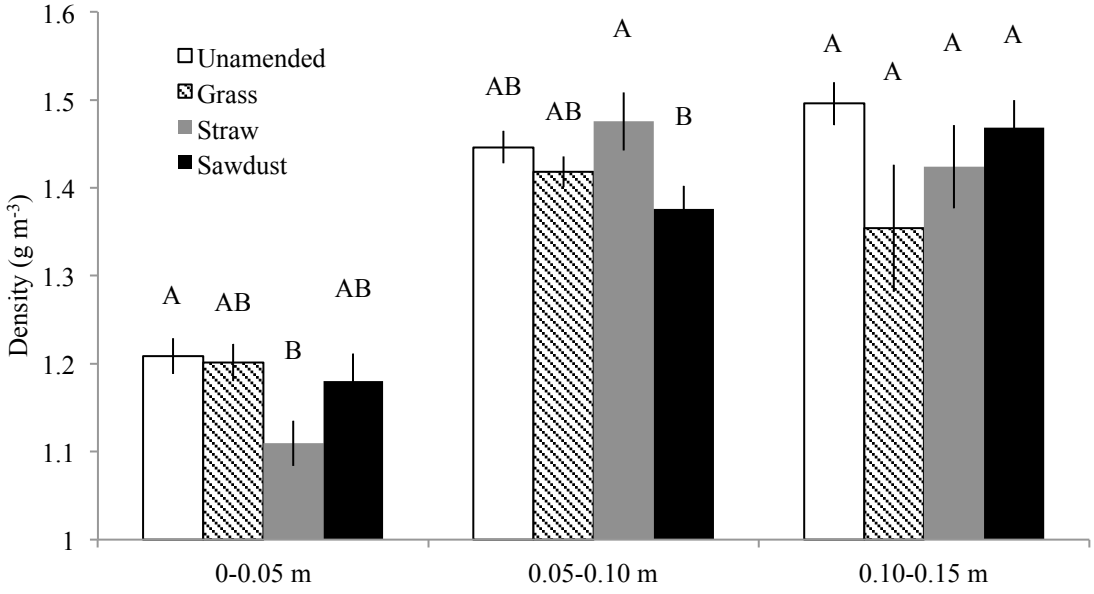

Figure 2.9 Mean soil bulk density based on soil amendment in 2014. Error bars are standard errors. Bars labeled with different letters are significantly different from other bars within the cluster based on a Tukey's HSD test ($p < 0.05$).

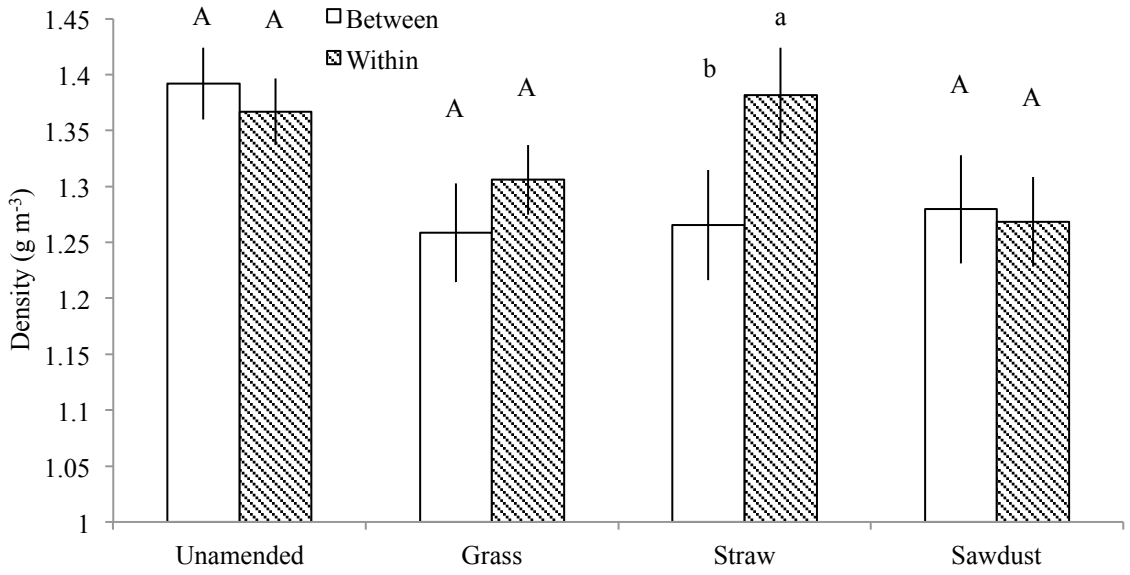

Figure 2.10 Mean soil bulk density based on sample location and soil amendment in 2015. Error bars are standard errors. Bars labeled with different letters are marginally different from the other bar within the cluster based on a Tukey's HSD test ($p < 0$

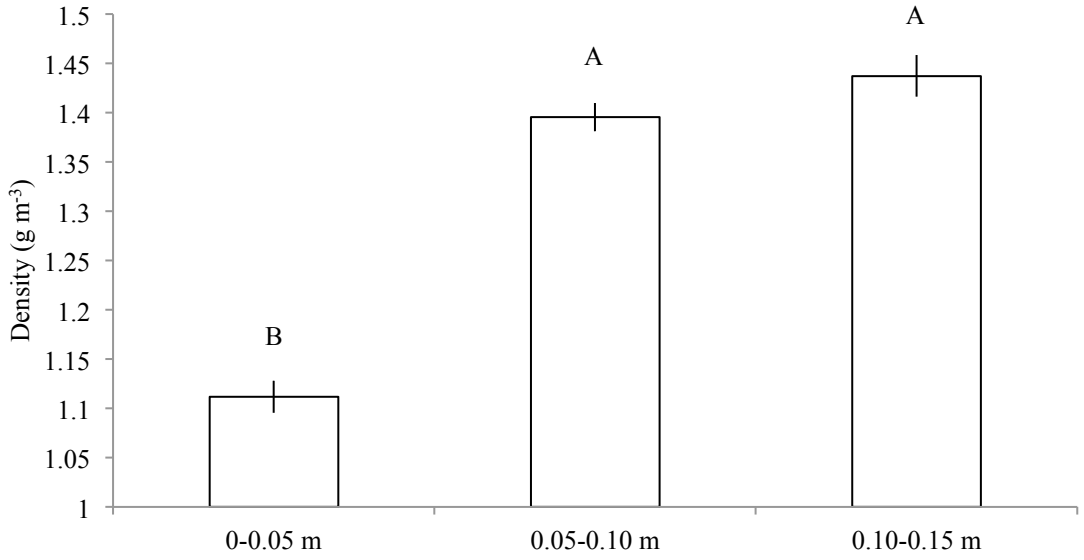

Figure 2.11 Mean soil bulk density based on sample depth in 2015. Error bars are standard errors. Bars labeled with different letters are significantly different from other bars based on a Tukey's HSD test ($p < 0.05$).

All soil health variables were run through a correlation matrix to see if there were any issues with co-linearity. All correlations were below 0.68 (Table 2.4). A principal component analysis was run to see if the soil health indicator tests were measuring the same soil qualities, but each principal component was comprised of at least 96% of one indicator, suggesting that each soil test looks at a different soil function (Table 2.5).

Table 2.4 Correlation matrix of soil health variables.

	Respiration	PMN	C:N Ratio	Soil Moisture
PMN	0.68			
C:N Ratio	0.38	0.25		
Soil Moisture	0.53	0.7	0.29	
pH	-0.03	-0.25	-0.07	-0.04

Table 2.5 Principal Component Analysis loadings of soil health parameters.

	Comp. 1	Comp. 2	Comp. 3	Comp. 4	Comp. 5
Respiration	96%				
PMN				94%	
C:N Ratio			99%		
Soil Moisture		96%			
pH					95%

Yield

Straw-amended soil had lower marketable yield than the grass- and sawdust-amended soils (Table 2.7). Straw-amended plots also had lower plant density than grass-amended plots (Table 2.7) so when yield was analyzed on a plant density basis, there was no difference in yield per plant (Figure 2.12, $F_{3,28}=1.21$, $p = 0.3$). Straw also had the lowest amount of rotten and damaged berries (Table 2.7). Despite differences in density and yield, there were no differences in foliar N in 2015 (Table 2.6). Tillage depth had no effect on any plant growth variables (Table

2.6). Foliar nutrient analysis stayed within recommended ranges in both 2014 and 2015 (Table 2.8).

Table 2.6 Plant growth and yield ANOVA based on soil treatments. $P < 0.05$ are significant and reported below, all non-significant treatment effects are noted with an "ns."

	Total Yield (kg ha^{-1})	Marketable Yield (kg ha^{-1})	Rotten Fruit (%)	Density (crowns m^{-2})	Foliar N 2015 (g m^{-2})
Amendment	<0.001	<0.001	0.001	0.02	ns
Tillage Depth	ns	ns	ns	ns	ns
Interaction	ns	ns	ns	ns	ns

Table 2.7 Plant growth and yield means as affected by soil amendments. Means that are statistically different from others in the column based on a Tukey's HSD test ($p < 0.05$) are labeled with different letters.

	Total Yield (t ha^{-1})	Marketable Yield (t ha^{-1})	Unmarketable Yield (%)	Plants Density 2015 (crowns m^{-2})	Foliar N 2015 (g m^{-2})
Unamended	68 **b**	56 **ab**	18 **a**	28 **ab**	2.4 **a**
Grass	79 **a**	64 **a**	19 **a**	33 **a**	2.7 **a**
Straw	53 **c**	48 **b**	9.8 **b**	19 **b**	1.8 **a**
Sawdust	70 **ab**	60 **a**	14 **ab**	26 **ab**	1.9 **a**

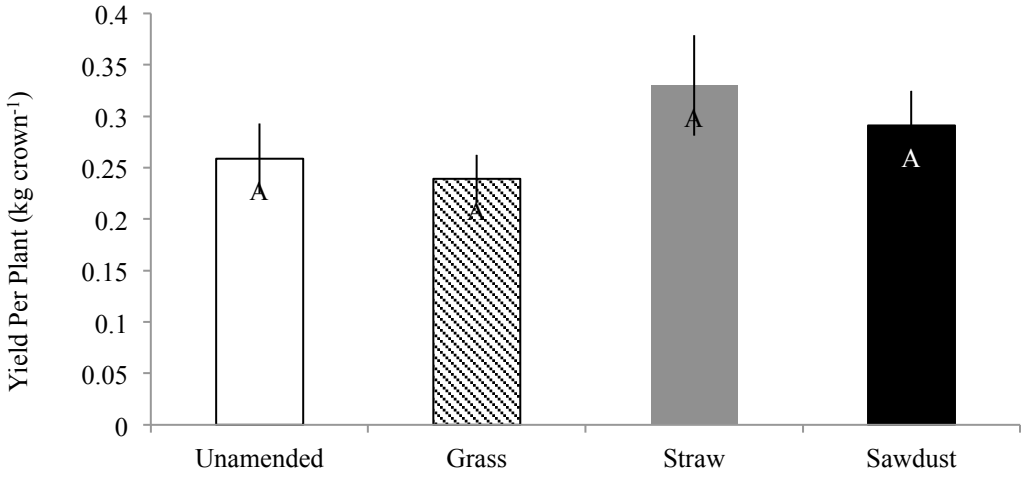

Figure 2.12 Mean yield per plant of grass-, straw-, sawdust-, or unamended plots. Bars labeled with different letters are significantly different based on a Tukeys HSD test ($p < 0.05$).

Table 2.8 Mean foliar nutrient concentrations and standard error for leaves collected in August 2014 and July 2015 from the strawberry field in Ithaca, NY. Values are reported as either percent or parts per million (1 ppm = 1 mg kg^{-1}) of total dry weight (n=4).

2014	Unamended		Grass		Straw		Sawdust	
Nutrient	Deep Till	Shallow Till	Deep Till	Shallow Till	Deep Till	Shallow Till	Deep Till	Shallow Till
Potassium (%)	1.7	1.7	1.5	1.5	1.7	1.6	1.9	1.6
Standard error	0.16	0.28	0.097	0.064	0.16	0.052	0.16	0.066
Phosphorus (%)	0.27	0.27	0.29	0.29	0.3	0.33	0.32	0.31
Standard error	0.019	0.036	0.026	0.0085	0.034	0.0075	0.0087	0.0084
Calcium (%)	1.7	1.7	1.3	1.3	1.7	1.36	1.4	1.3
Standard error	0.25	0.19	0.025	0.04	0.19	0.05	0.19	0.045
Magnesium (%)	0.4	0.43	0.42	0.41	0.4	0.42	0.42	0.44
Standard error	0.025	0.043	0.012	0.01	0.013	0.0067	0.023	0.0052
Boron (ppm)	30	34	30	32	31	33	35	33
Standard error	1.3	4.4	3.4	4	4.4	1.1	1.7	2.5
Manganese (ppm)	61	94	64	70	100	97	63	69
Standard error	12	21	8.4	15	11	4.7	7	11
Iron (ppm)	140	130	150	180	320	180	98	170
Standard error	28	45	19	21	100	19	18	31
Copper (ppm)	6.8	6.5	7	6.9	7	6.8	7.1	7.1
Standard error	0.18	0.22	0.064	0.23	0.32	0.073	0.097	0.19
Zinc (ppm)	21	30	22	20	23	23	24	23
Standard error	1.2	10	1.2	0.78	0.85	1.3	0.96	0.82

2015	Unamended		Grass		Straw		Sawdust	
Nutrient	Deep Till	Shallow Till	Deep Till	Shallow Till	Deep Till	Shallow Till	Deep Till	Shallow Till
Potassium (%)	1.7	1.9	2.1	1.5	2.3	1.9	2	1.8
Standard error	0.11	0.17	0.11	0.064	0.16	0.05	0.08	0.2
Phosphorus (%)	0.29	0.26	0.29	0.3	0.26	0.29	0.27	0.26
Standard error	0.015	0.02	0.024	0.022	0.0091	0.0058	0.0037	0.013
Calcium (%)	1.4	1.8	1.9	1.73	1.9	1.8	2	1.9
Standard error	0.19	0.21	0.12	0.15	0.085	0.047	0.062	0.2
Magnesium (%)	0.4	0.38	0.37	0.4	0.38	0.38	0.38	0.37
Standard error	0.023	0.018	0.017	0.028	0.012	0.0056	0.0073	0.017
Boron (ppm)	34	31	34	35	36	31	34	31
Standard error	1.6	2.1	1.8	2.2	1.8	0.62	1.4	1.3
Manganese (ppm)	77	59	57	61	110	50	58	48
Standard error	15	13	8.9	8	44	6.8	12	3.6
Iron (ppm)	130	150	100	130	190	200	120	120
Standard error	43	51	27	33	40	14	40	46
Copper (ppm)	6.3	5.7	5.8	5.9	6.4	5.7	5.9	5.5
Standard error	0.59	0.2	0.33	0.28	0.41	0.12	0.067	0.19
Zinc (ppm)	22	21	222	22	25	22	22	21
Standard error	0.17	1	1.3	0.7	2.8	0.51	1.2	0.9

To see if soil health indicators were correlated with yield another generalized linear model was run with yield as the dependent variable. All the soil health variables were tested as independent variables with between the rows and within the rows tested separately. There were some significant correlations; however, no pattern emerged (Table 2.9).

Table 2.9 Soil health variables from both between the rows and within the rows correlated with plant growth and yield. Soil health variables that are significantly correlated with yield are shown ($p < 0.05$). Non-significant correlations are noted with an "ns."

		Variables				
Sample Date		**Respiration**	**PMN**	**C:N**	**Soil Moisture**	**pH**
5/1/14	Total Yield	ns	ns	ns	ns	Ns
Between	Marketable Yield	ns	ns	ns	ns	ns
	Percent Rot	ns	ns	ns	ns	0.04
6/17/14	Total Yield	ns	ns	ns	ns	ns
Between	Marketable Yield	ns	ns	ns	ns	ns
	Percent Rot	ns	0.008	ns	ns	ns
Within	Total Yield	0.002	ns	ns	ns	ns
	Marketable Yield	0.01	ns	ns	ns	ns
	Percent Rot	0.003	ns	ns	ns	ns
9/24/14	Total Yield	ns	0.02	ns	ns	ns
Between	Marketable Yield	ns	0.006	ns	ns	ns
	Percent Rot	0.0006	ns	ns	ns	ns
Within	Total Yield	ns	ns	ns	0.03	ns
	Marketable Yield	ns	ns	ns	ns	ns
	Percent Rot	ns	ns	ns	0.04	ns
5/19/15	Total Yield	ns	0.04	ns	ns	ns
Between	Marketable Yield	ns	ns	ns	ns	ns
	Percent Rot	ns	ns	ns	ns	ns
Within	Total Yield	ns	ns	ns	ns	ns
	Marketable Yield	ns	ns	ns	ns	ns
	Percent Rot	ns	ns	ns	ns	ns
8/19/15	Total Yield	ns	ns	ns	0.008	ns
Between	Marketable Yield	ns	ns	ns	0.01	ns
	Percent Rot	ns	ns	ns	ns	ns
Within	Total Yield	ns	ns	ns	ns	0.04
	Marketable Yield	ns	ns	ns	ns	0.03
	Percent Rot	ns	0.01	ns	0.04	ns

DISCUSSION

A Story Beyond C and N

The results of the soil health indicator tests show that the effects of the soil amendments on the soil was not simply a C story, a N story, or a C:N ratio story. Both C and N and their relative amounts were important qualities of a soil amendment, but they were not the only important soil qualities. This is supported by research where N content, lignin, water soluble N, cellulose, phenolic acids, and the C:N ratio were all shown to be important factors in amendment decomposition (Bengtsson et al. 2003, Frankenberger and Abdelmagid 1985, Martens 2000).

Despite the fact that the C:N ratio of the soil did not change when amendments with highly variable C:N ratios were added to the soil, both respiration and PMN did increase from unamended soil (Table 2.2). In general, respiration tended to be higher with higher C additions from amendments with higher C:N ratios. Sawdust and straw usually had the highest respiration rates (Figure 2.3), which were also the amendments with the highest C:N ratios and C additions (Table 2.1). The increased in microbial activity due to C additions caused soil microbes to respire more and mineralize N more quickly. However, the C and N were not the only factors at play. Per kg of C added to the soil, sawdust-amended soils increased respiration more than other soil amendments (Figure 2.4). Similarly, per kg of N added to the soil, sawdust-amended soils increased PMN more than other amendments (Figure 2.6). Both respiration and PMN increased more than the increase in C or N (respectively) in the sawdust, when it was added to the soil. This indicates that the C and N from sawdust supported a greater increase in microbial activity than the C and N from the grass or straw. One potential reason for increased respiration per kg of added C is the priming effect. The priming effect is the change in soil organic matter mineralization from the addition of organic amendments (Wang et al. 2015). This study did not

differentiate between soil organic matter and amendment mineralization; however, the increased CO_2-C may have come from soil C rather than relying solely on amendment C. Other studies have also found that amendments with higher C:N ratios have resulted in higher positive priming effect (Potthast et al. 2010), especially in the long term (Wang et al. 2015). The sawdust amendment was also the finest soil amendment and therefore its incorporation into the soil may have formed a greater number of detritusphere microbial hotspots with increased microbial activity (Kleber et al. 2015). Alternatively it is possible that the nutrients in sawdust were more available to the soil microbial community, whether due to amendment chemistry (Moorhead and Sinsabaugh 2006), microbial disposition to decompose that form of C and N (Scheller and Joergensen 2008), or some other amendment property.

Soil Health Indicator Tests and Yield

The particular set of soil health indicator tests used in this study did illuminate some changes in soil chemical, physical, and biological properties due to the treatments; however, none of these changes were indicative of changes in yield. Strawberries grown in straw-amended soil were not as dense as strawberries in other treatments, and therefore yield was significantly lower (Table 2.6), but none of the soil health indicator tests were correlated with this lower yield (Table 2.8). Although it is true that a "soil health" test should not only look at yield because it would then simply be a soil productivity test (Wander and Drinkwater 2000), it is also critical to include yield since a grower cannot be expected to subsidize "soil health" (Doran 2002, Wander and Drinkwater 2000). Ideally soil health indicator tests would identify potential issues before they have an economic impact on the grower, but in this experiment the tests did not. Other experiments in perennial cropping systems also had issues correlating soil

health and instead judged soil health indicator tests on their ability to detect management differences (Glover et al. 2000, Leinfelder 2010). While increasing soil biological activity may lead to increased environmental services, it is not realistic to give that responsibility to growers. Also, it would be more beneficial to clearly define the goals of a soil, such as yield and decreased need for external inputs, and choose soil health indicator test based on correlations with those goals. Since these correlations have not yet been found for perennial systems, perhaps the most informative soil health indicator tests are not yet being used in current soil heath research.

Sample Collection Methods

The soil health indicator tests also show that sample collection method matters. Whether soil samples are collected between or within the rows can affect pH and density. It may be important in the future to sample on a volumetric basis rather than a depth basis because density was highly variable based on tillage depth, sample location, and soil amendment. Sampling soils of different densities on a depth basis results in collecting different amounts of soil, and the concentrations of nutrients varies based on soil profile depth, leading to misleading nutrient data (Wuest 2009). Similarly, pH was lower within the rows than between the rows from a combination of plant nutrient uptake and fertilization. As plants take up nutrients they release H^+ ions, decreasing pH over time (Randall et al. 2006, Wang et al. 2006). Also, the field was fertilized with urea, which acidifies the soil (Cai et al. 2014, Jiang et al. 2014). Fertilizer was only applied in banded strips next to the strawberries and therefore only affected within row soil. Since nutrients are only available to plants at specific pH ranges, it is important to have accurate pH information from soil collected within the rows.

When the soil was sampled also played a role in whether there were differences between treatments. Late fall applied soil amendments had no differences between treatments by the fall of the next year, and different tillage treatments showed no differences within the two years of the study. This is consistent with other short-term studies that were unable to find differences in microbial indicators in reduced tillage treatments (Tillman et al. 2015, Vakali et al. 2014). Depending on the management practice a grower is interested in testing to see if it is improving or degrading their strawberry field, effective and illuminating sample collection times may vary.

A standardized soil sampling protocol, specific about where, when, and how to sample, should be refined so that results from different strawberry farms may be most informative and directly compared to each other.

CONCLUSIONS

In this experiment the chosen soil health indicator tests were responsive to different soil amendment treatments, giving some insight into microbial activity based on soil amendment qualities beyond the C:N ratio. However, none of the soil health indicator tests responded to different tillage depths, and none were correlated with the decreased growth and yield in straw-amended plots. Perennial crops may require a different set of soil health indicator tests to be more useful for growers. Additionally, specific sample collection procedures should be developed in order to ensure that results are informative and consistent.

Using Straw

Further research should also be done to try to pinpoint the negative interaction between plant growth and straw-amendment. A grower should not stop using mulch altogether until a

better alternative is found. It is important to recognize that straw is having a negative effect on strawberry plant growth because this will motivate the search for a better cultural practice. However, it is also important to recognize all benefits of straw and not switch mulches before an adequate replacement can be found. Straw has excellent insulative properties and therefore growers use it to protect their plants from cold damage (Boyce 1991, Carroll et al. 2013). Straw is also a protective layer between the ground and the berries, reducing strawberry diseases carried in the soil such as leather rot (Ellis et al. 1998). There was significantly less rotten and damaged fruit in straw amended plots, which supports the idea that straw protects berries from soil-borne disease.

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CHAPTER 3

WHEAT STRAW EFFECTS ON STRAWBERRY GROWTH IN THE GREENHOUSE

ABSTRACT

Strawberry growers in cool climates cover their field with straw to insulate it during the winter. However, when conducting a field experiment looking at effects of different soil amendments on the soil health in strawberry fields, strawberries grown in straw-amended soil had lower plant density and yield than unamended soil. Three hypotheses for this reduced growth were that a chemical leachate in the straw was having a phytotoxic effect on the strawberries, that the specific soil microbiome was inhibiting growth, or that straw was physically blocking roots from easily penetrating into the soil. Eight greenhouse treatments were used to tests these hypotheses. Un-mulched and regular straw mulch treatments were compared to see if reduced plant growth from straw could be replicated in the greenhouse. Un-mulched strawberries watered with straw leachate, and strawberries mulched with leached straw were compared to test the chemical leachate hypothesis. Strawberries planted in autoclaved soil and straw mulch, and planted in autoclaved soil and straw mulch that was then re-inoculated with the native soil microbiome were compared to test the microbial hypothesis. Unamended and straw-amended strawberries were compared to test the physical straw barrier hypothesis. 'Honeoye' strawberries were used to test the straw physical barrier hypothesis and 'Cavendish' were added for all other treatment comparisons to test variety responses. All strawberries were planted in a mixture of field soil and potting mix. Leaf area or mass was measured to determine plant growth. There were no differences in leaf area and mass between any of the treatments, but there were differences between varieties. 'Cavendish' had greater leaf area than 'Honeoye' in the

autoclaved and re-inoculated treatments, but ‘Honeoye’ had greater leaf area than ‘Cavendish’ in all other treatments.

INTRODUCTION AND HYPOTHESES

Strawberries are an important crop worldwide, in 2011 an estimated 4,594,540 metric tons of strawberries were produced (Boriss et al. 2014). In the United States alone strawberries are worth $2,391,406 thousand (Perez and Plattner 2014). Growers in cool climates often cover their fields with wheat straw, which has good insulative properties (Boyce 1991, Kumar and Dey 2011), to protect their strawberries during the winter (Carroll et al. 2013, Pritts and Handley 1998). Straw also provides a barrier between the berries and the soil, reducing fungal fruit diseases (Ellis et al. 1998). However, during a field experiment looking at the effects of different soil amendments on soil biological health, strawberry plant density and yield were lower in straw-amended soil. Plants were also visibly smaller and runnered less than strawberries grown in grass-, sawdust-, or unamended soil. If straw was found to have adverse effects on strawberry plant growth, a replacement winter-insulator and mulch would have to be found, but first the effect must be replicated, and understood. There were three hypotheses about this observed reduced growth.

The chemical hypothesis was that a leachate from the wheat straw had a phytotoxic effect on strawberry plant growth since it has been found to have a phytotoxic effect on other plant species. In perennial ryegrass, a greater proportion of straw leachate used to water the plants reduced root length (Hamdi et al. 2001). Phenolic acids, especially p-coumaric acid, have been implicated as the chemicals responsible for these allelopathic interactions (Guenzi and McCalla 1966).

The biological hypothesis was that the soil microbiome created by the interaction between the straw amendment and the soil was impeding strawberry growth. Microbiomes can have far-reaching effects on overall plant health and productivity (Chaparro et al. 2012). For example, they have been shown to effect flowering time, drought tolerance, and disease resistance (Panke-Buisse et al. 2014, Mendes et al. 2011, Lau and Lennon 2012). Often the specific mechanisms for these microbiome- plant interactions are unknown (Panke-Buisse et al. 2014) but the known modes of influence are through microbial decomposition, nutrient solubilization, nutrient cycling, plant hormone secretion, pathogen antagonism, and plant immune system induction (Lakshmanan et al. 2014). Soil microbiomes have been shown to be influenced by soil properties such as C:N ratio and pH (Zarraonaindia et al. 2015). It is possible that straw changed a property of the soil, which then fostered the growth of a soil microbiome unfavorable to strawberry growth.

The physical barrier hypothesis was that the incorporated straw interfered with root development and normal plant growth. Other bulky soil constituents have been found to impeded plant growth, so it is conceivable that straw can do that same. Martre et al. (2002) found that *Agave deserti* and *Pleuraphis rigida* both had higher leaf area in less rocky soils.

These hypotheses were tested in a greenhouse, where the first goal was to reproduce the poor growth effect observed in the field. The prediction was that if repressed plant growth was due to a chemical leachate, then watering the strawberries with a straw leachate would repress plant growth but mulching strawberries with leached straw would not. If instead the biological hypothesis was correct, repressed plant growth would not be seen with strawberries grown in autoclaved soil but growth would be repressed in soil re-inoculated with soil microbes. If straw was simply causing a physical barrier to normal plant growth, then there would be reduced

growth in pots where straw was incorporated into the pot, but not in pots without straw. Two strawberry varieties were planted because different strawberry genotypes react to different environments in a variety of ways and what may be an issue in one variety is not an issue in another (Hokanson and Finn, 2000). The two varieties were predicted to have different growth habits and react to the treatments differently.

MATERIALS AND METHODS

Experiment 1

Eight treatments were established as described in Table 3.1. The control and straw mulch treatments tested if repressed plant growth could be replicated in the greenhouse. The leachate and leached straw treatments were run to see if a chemical leachate in the straw had a phytotoxic effect on strawberry plants, autoclaved and re-inoculated treatments examined if microbes were immobilizing N in the soil, and straw-amended and unamended treatments examined if straw physically blocked strawberry growth. 'Honeoye' and 'Cavendish' strawberry varieties were compared in the first six treatments. Both are popular, mid-season varieties except 'Cavendish' is resistant to red stele and verticillium wilt and 'Honeoye' is the variety first noticed to have reduced plant growth in the field. Only 'Honeoye' strawberries were used to test the physical barrier hypothesis.

For the first six treatments 3.79 L pots were filled with a mixture of 1:1 v:v soil collected from East Ithaca and Cornell Mix potting soil. Ten replicates of 'Honeoye' and 'Cavendish' strawberries were planted for each of the six treatments for a total of 120 pots. All strawberries were planted within three days of each other. Plants were given 17 days to establish and then pots were mulched with 22 ± 2 g of dry weight mulch. For the autoclaved and re-inoculated treatments, field soil was autoclaved for 4 hours at 120°C then mixed with potting soil. Re-

inoculated pots were treated 33 days after planting with 25 mL of a slurry of 1:10 v:v solution of field soil:solution. The autoclaved treatment was instead treated with 25 mL of autoclaved soil slurry to prevent introduction of microbes. The greenhouse remained at 21°C during the day and between 18°C-21°C during the night. Pots were randomly arranged on the bench and were re-arranged every 14 ± 1 days. To water, 5 pots were randomly selected and watered to just beyond field capacity. Those water volumes were averaged and about 20 mL of water was subtracted from the average. Each remaining pot was watered with that final amount. A 1:6 v:v straw leachate:water solution was mixed to water all the leachate pots.

Pots were watered when the majority needed water to prevent overwatering. Since two treatments (control and leached straw) did not have mulch, they experienced increased evaporation and were slightly water stressed. A few alternative mulches were tried in order to reduce evaporation. A layer of tin-foil topped with a paper plate, reducing reflection, was used to mulch the control and leached straw treatments 32 days after planting.

Four months after planting total leaf area was measured by cutting all leaves from the plants and a day later, running them through an area meter. Leaf area was used as an indicator of plant growth. A two-way ANOVA was run to determine if the treatments had an effect on leaf area. Linear contrasts were run to determine if pairs of treatments: control vs. straw mulch, re-inoculated vs. autoclaved, and leached straw vs. leachate were different from one another. Linear contrasts were also used to determine if there was a difference between 'Cavendish' and 'Honeoye' strawberry varieties within each treatment pair.

Experiment 2

For the unamended and straw-amended treatments 152 mm pots were either filled with a mixture of 1:1 v:v soil collected from East Ithaca and Cornell Mix potting soil or 1:1:1 v:v:v soil potting mix and wheat straw. Eleven replicates of 'Honeoye' strawberries were planted for each treatment and one straw-amended plant died for a total of 21 pots. All strawberries were planted on the same day. The greenhouse remained at 21°C during the day and between 18°C-21°C during the night. Pots were randomly arranged on the bench and watered as needed with reverse osmosis water. Four months after planting all leaves were cut from the plants and put in the oven at 50°C until dry. Leaves were weighted to determine plant growth. An ANOVA determined if the treatment had an effect on total leaf mass. A Tukey's HSD test determined which treatments were different from one another.

Table 3.1 Treatment pairs used to test the chemical, biological, and physical hypotheses.

Treatment	Name
Strawberries planted in an un-mulched control	Control
Strawberries mulched with straw	Straw Mulch
Strawberries mulched with leached straw	Leached Straw
Un-mulched strawberries watered with straw leachate	Leachate
Strawberries planted in autoclaved soil and mulched with autoclaved straw that was then re-inoculated with the native soil microbes	Re-inoculated
Strawberries planted in autoclaved soil and mulched with autoclaved straw	Autoclaved
Strawberries planted in unamended soil	Unamended
Strawberries planted in straw-amended soil	Straw-amended

RESULTS

First the control and straw mulch treatments were compared to see if repressed strawberry plant growth from straw, observed in the field, could be replicated in the greenhouse. After model simplification these treatments had the same leaf area (Table 3.2 t = -0.07, $p = 0.9$), and 'Honeoye' had higher leaf area than 'Cavendish' (Table 3.2 t = -3, $p = 0.006$). The leachate

and leached straw treatments had the same leaf area (Table 3.2 t = -0.05, $p = 1$), and 'Honeoye' had higher leaf area than 'Cavendish' (Table 3.2 t = -2, $p = 0.02$). The autoclaved and re-inoculated treatments had the same leaf area (Table 3.2 t = 0.2, $p = 0.8$) and 'Cavendish' and 'Honeoye' strawberry plants had the same leaf area (Table 3.2 t = 2, $p = 0.1$). The unamended and straw-amended treatments had the same leaf mass (Table 3.2 $F_{1, 19} = 0.03$, $p = 0.9$).

Table 3.2 Comparisons of treatments and varieties using linear contrasts and Tukey's HSD test. Test statistics and *p* are show and statistically significant comparisons ($p < 0.05$) are marked with an *

Comparisons			**t value or F statistic**	***p***
Control	vs	Straw Mulch	t = -0.07	1.0
'Cavendish'	vs	'Honeoye'	t = -3	0.03 *
Leachate	vs	Leached Straw	t = -0.05	1.0
'Cavendish'	vs	'Honeoye'	t = -2	0.10
Autoclaved	vs	Re-inoculated	t = 0.2	1.0
'Cavendish'	vs	'Honeoye'	t = 2	0.5
Unamended	vs	Straw-amended	$F_{1,19} = 0.03$	0.9

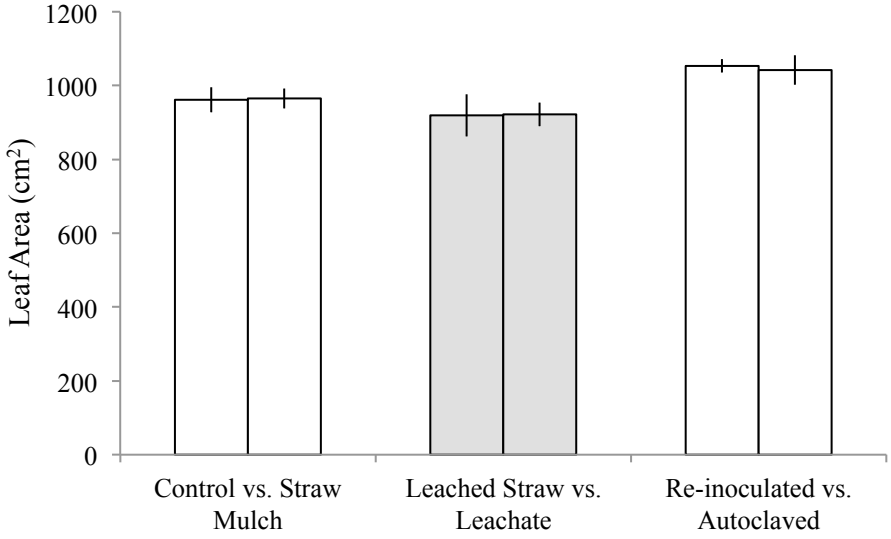

Figure 3.1 Graph of means and standard errors of leaf areas (cm^2) of six greenhouse straw mulch treatments compared in pairs.

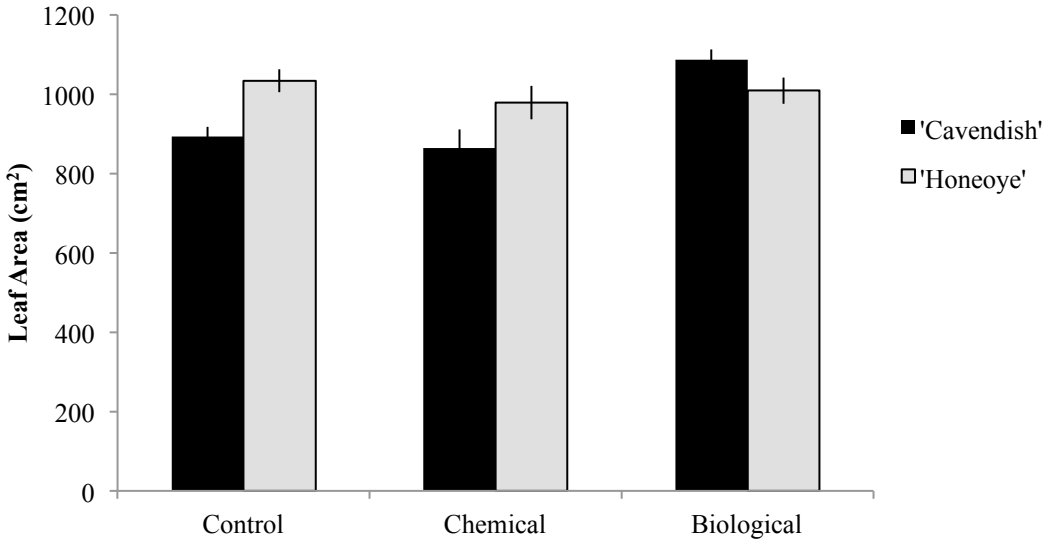

Figure 3.2 Graph of means and standard errors of leaf areas (cm^2) of 'Honeoye' and 'Cavendish' strawberry varieties grown with six different treatments compared in pairs. The control pair compared the control and straw mulch treatments. The chemical pair

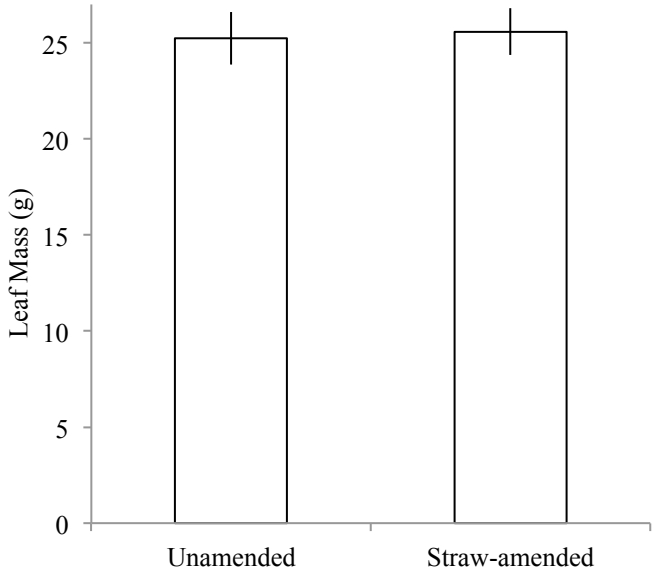

Figure 3.3 Graph of means and standard errors of leaf areas (cm^2) of two greenhouse treatments: unamended and straw-amended**.**

DISCUSSION AND CONCLUSION

The effect seen in the field was not replicated in the greenhouse since there was no difference in leaf area between the control and straw mulch treatments. There was also no difference in leaf area between the re-inoculated and autoclaved, leached straw and leachate treatments, or the unamended and straw-amended treatments. Therefore none of the hypotheses were supported by these data and these results did not yet pinpoint the mechanism causing strawberries in straw-amended soil to have reduced density and yield in the field.

Greenhouse conditions are inherently different from field conditions so finding a way to induce reduced plant growth, similar to what was observed in the field, can be a challenge. In this case, in the field, soil amendments were incorporated into the soil in the fall before strawberries were planted in the spring. It is possible that the observed reduced growth was due to the long incubation period between incorporation and planting.

This experiment did highlight distinctions in strawberry varieties because the varieties had different responses to the treatments. 'Honeoye' strawberries had greater leaf area than 'Cavendish' in the control vs. straw mulch and, leachate vs. leached straw treatments but not in the autoclaved vs. re-inoculated treatments. 'Honeoye' strawberries are less disease resistant than 'Cavendish' (Khanizadeh et al. 1992), which may explain 'Honeoye's' smaller leaf area in biological treatments. Also, 'Cavendish' strawberries generally produce larger fruit than 'Honeoye' (Khanizadeh et al. 1992), which may be due to more resources allocated to the fruit than the leaves. This would explain why 'Cavendish' leaves were usually smaller than 'Honeoye.'

Strawberry growers in NY are not yet advised to stop using straw mulch in their strawberry fields. The literature shows that straw effectively insulates and protects strawberries

from fruit rot (Boyce 1991, Ellis et al. 1998). Negative effects of straw on strawberry growth were not observed in this experiment, so it is not a omnipresent issue; however, research should continue to see if there is a way to induce the effect noticed in the field so that the cause could then be isolated.

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